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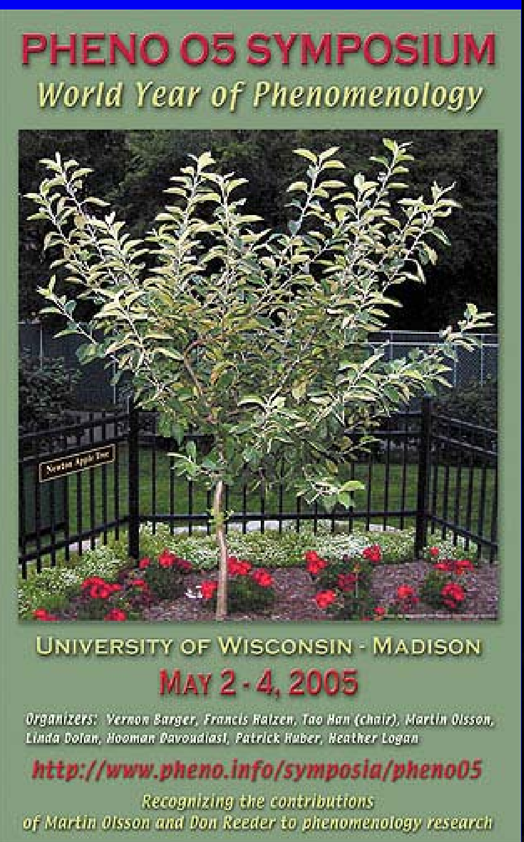


Neutrino Oscillation Experiments

Special Thanks to:
- B. Berger (KamLAND - Moriond2005)
- C. M. Cattadori (Radiochemical – Neutrino2004)
- M. Nakahata (SuperK – Neutrino2004)
- T. Nakaya (K2K – Neutrino2004 – hep0411038)
- C. Mariani (K2K – Moriond2005)
- Choji Saji (SuperK – ICHEP2004)

Outline

- Introduction
- Solar Neutrino Experiments
- Neutrinos produced at Reactors
- Atmospheric Neutrino Review
- Long baseline Neutrino Beams
- Summary and Conclusion

Neutrino Mixing

As in the quark sector one defines a neutrino mixing matrix which relates the mass and weak eigenstates

Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

	solar	atmospheric	CP violation	short-baseline
Quark:	$\theta_{12} \approx \pi / 14$	$\theta_{23} \approx \pi / 76$	yes	$\theta_{13} \approx \pi / 870$
Neutrino:	$\theta_{12} \approx \pi / 6$	$\theta_{23} \approx \pi / 4$	???	$\theta_{13} < \pi / 20$

$$U_{\alpha i} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

Neutrino Oscillations (2-flavor analysis)

$P_{\alpha\beta} = \sin^2(2\theta)\,\sin^2(1.27\Delta m^2\, L / E)$

- **Physics:**

  Δm^2 & $\sin(2\theta)$

- **Experiment:**

  Distance (L) & Energy (E)

$$\Delta m^2 \equiv \Delta m^2_{ij} \text{ and } \theta \equiv \theta_{ij}$$

3 Parameters !

$$\Delta m^2 = m_j^2 - m_i^2$$

$$\theta = \text{Mixing angle}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The state evolves with time or distance

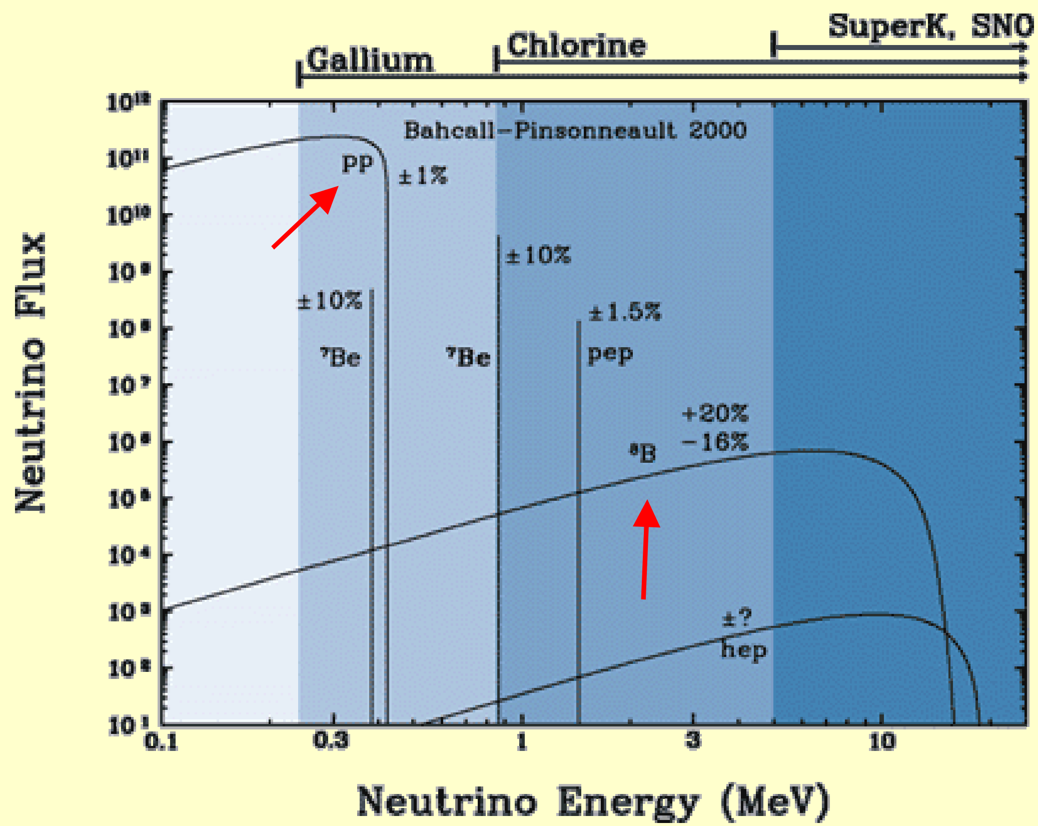
Solar Neutrino Experiments

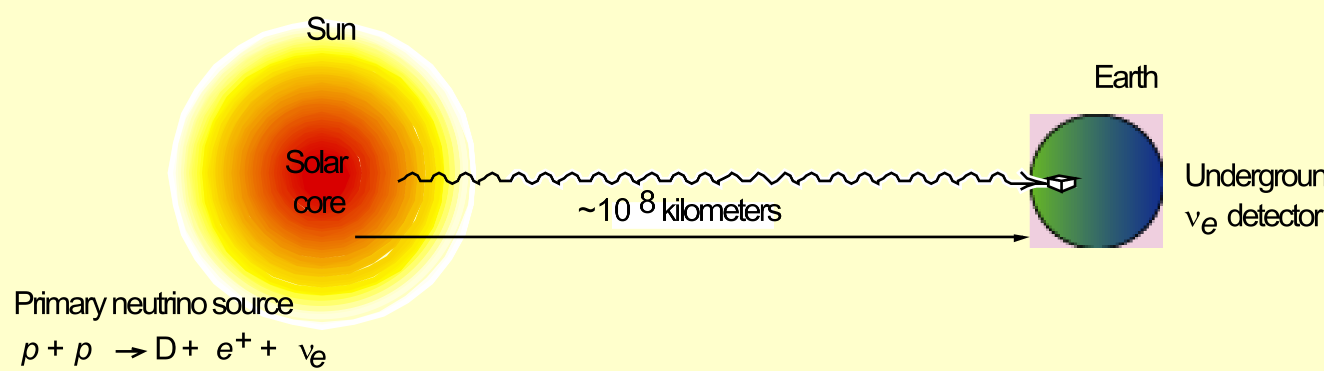
- Review of the Solar Standard Model (SSM)
- Radiochemical experiments: Chlorine – Gallium
- SuperKamiokande (some preliminary results)
- Sudbury Neutrino Observatory (Salt Results) NEW

Neutrino Production in the Sun

Light Element Fusion Reactions

★ $p + p \rightarrow {}^2H + e^+ + \nu_e$	99.75 %
$p + e^- + p \rightarrow {}^2H + \nu_e$	0.25 %
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	~10^{-5} %
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	15 %
★ ${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$	0.02 %





Chlorine Measurements: Homestake

- 1960's: $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$
- Depth: 4850 ft
- Detector fluid: 3.8×10^5 litres
- Energy Thresold: 0.814 MeV

  Sensitive to ^8B & ^7Be ν's

- **Observed rate (SNU)**

  2.56 ± 0.16(stat) ± 0.16(syst)

- **Expected rate (SNU)**

  $8.5^{+1.8}_{-1.8}$ **[1σ from BP2004]**

Gallium Experiments

$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

Radiochemical Target

Energy Threshold: 0.233 MeV

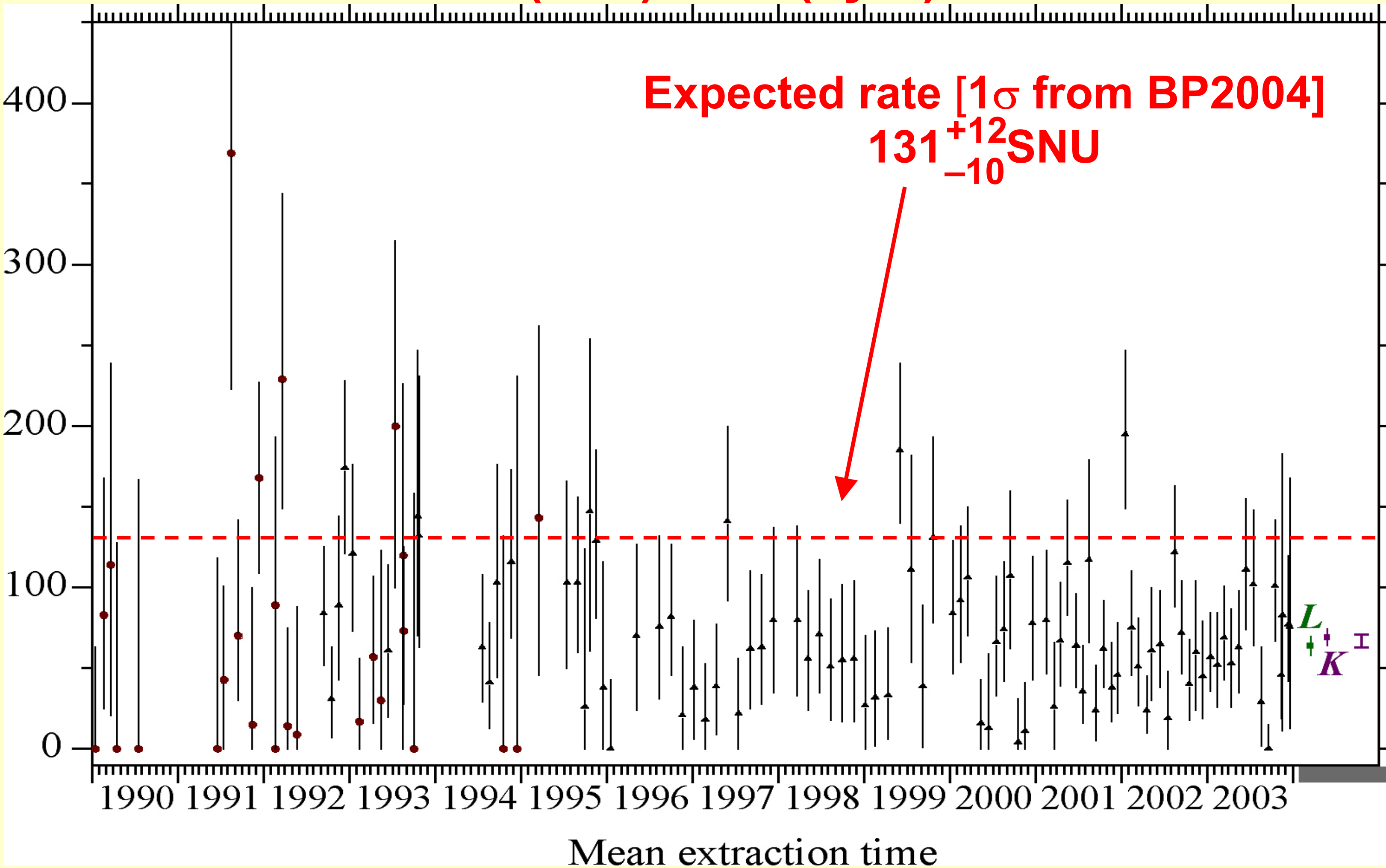
Small proportional counters are used to count the Germanium

Sensitive to pp, ^7Be, ^8B, CNO, and pep ν's

Gallium Measurements: SAGE (on-going)

SAGE overall 1990-2003 (121 runs)

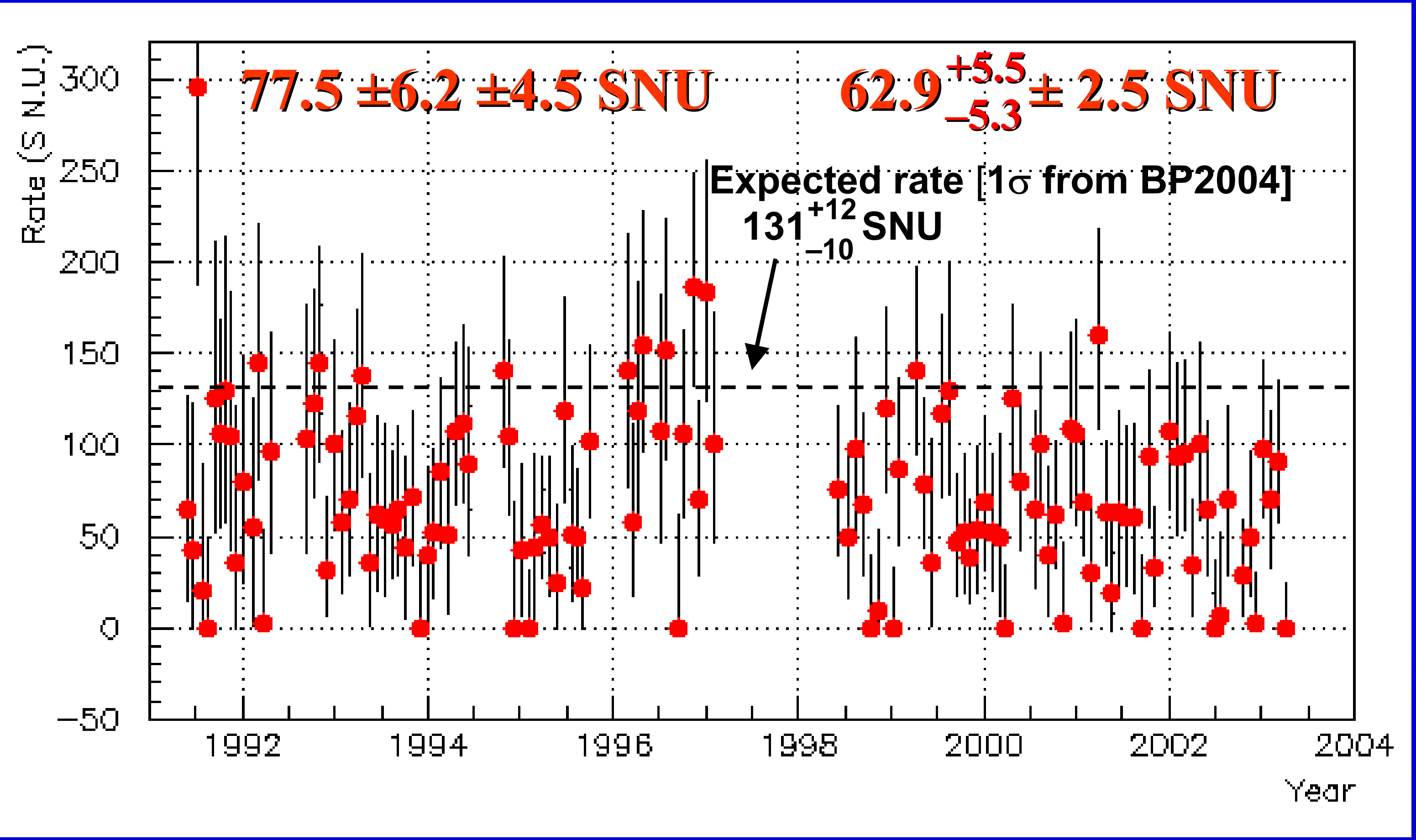
66.9 ±3.9 (stat) ±3.6 (syst) SNU



Source: Neutrino 2004

Gallium Measurements

GALLEX	GNO (terminated)
65 Solar runs = 1594 d	58 Solar runs = 1713 d
23 Blank runs	12 Blank runs



Source: Neutrino 2004

Water Detector: Super-Kamiokande

- ^{8}B neutrino measurement by

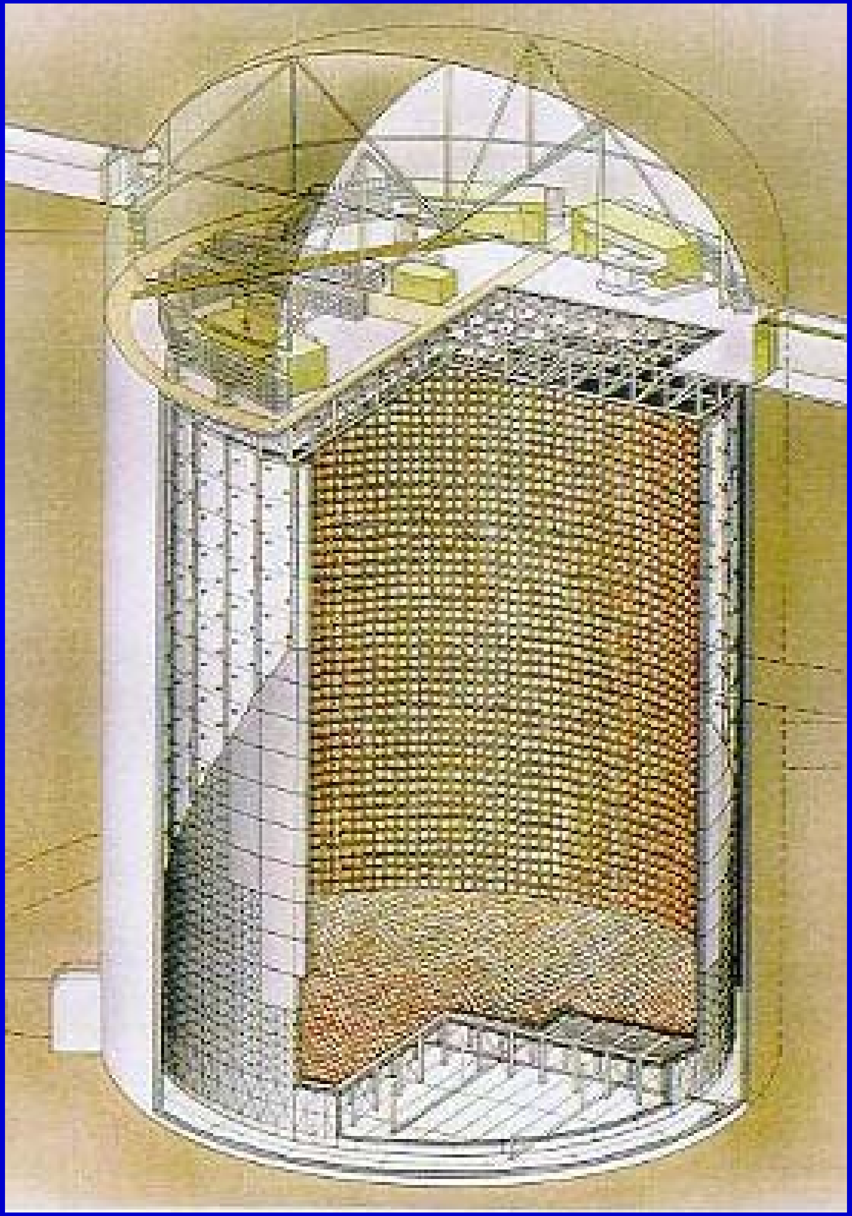
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

- Sensitive to ν_e, ν_μ, ν_τ

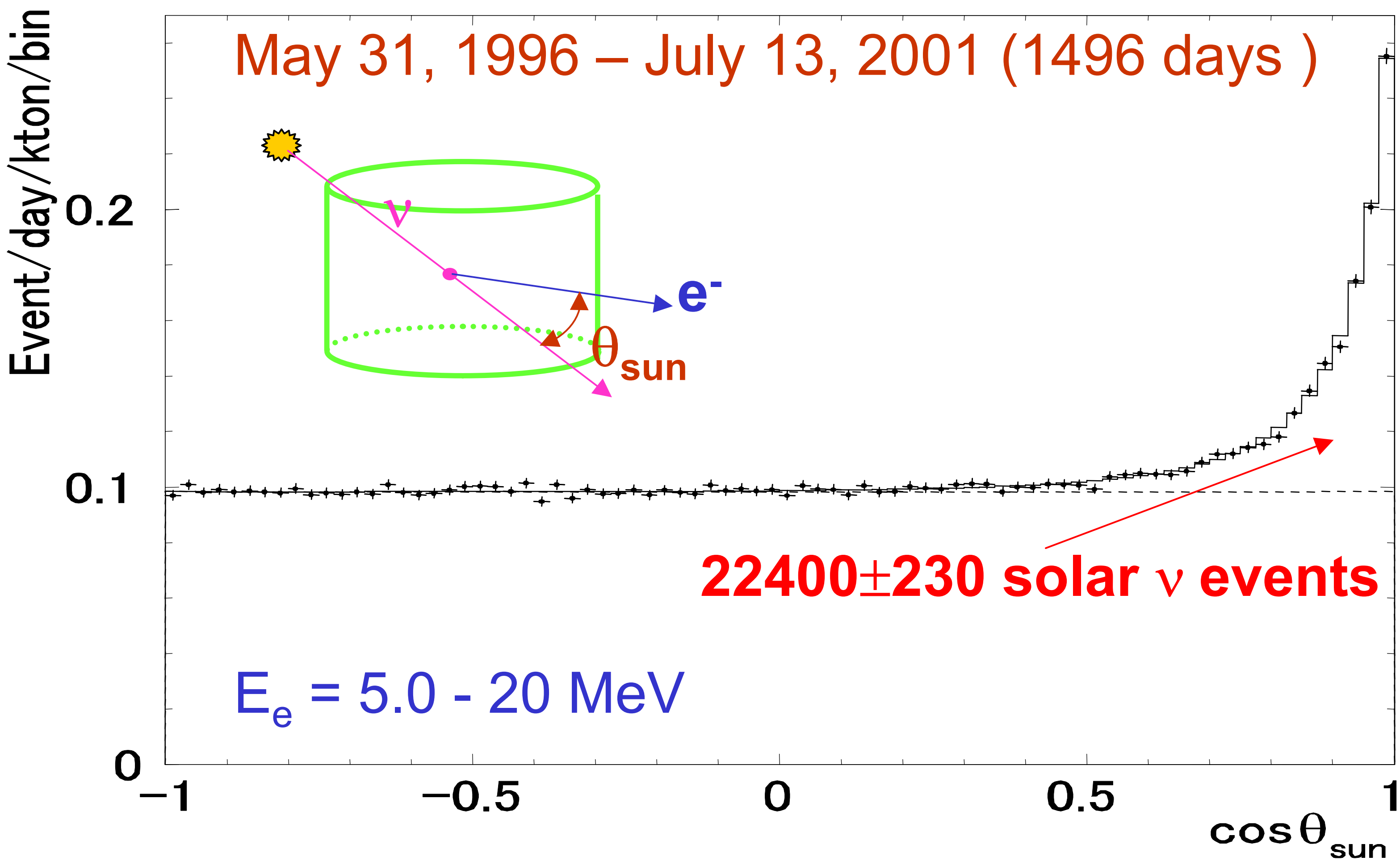
  $\sigma(\nu_{\mu,\tau} + e^-) \approx 0.15 \times \sigma(\nu_e + e^-)$

- High statistics ~15ev./day
- Real time measurement allow studies on time variations
- Studies energy spectrum

- 50 ktons of pure water with 11,146 PMTs (fiducial volume of 22.5 ktons for analysis)



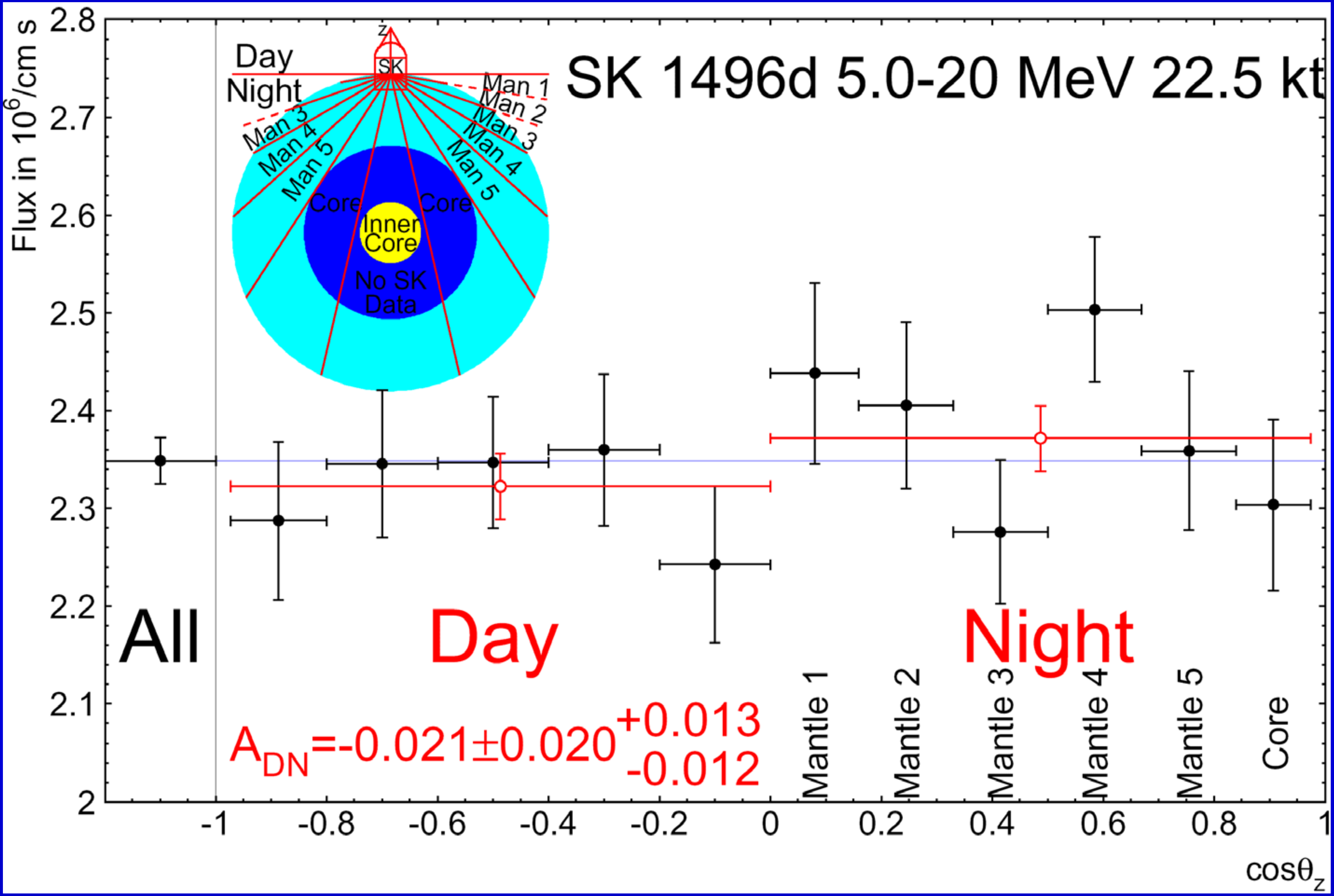
Solar neutrino data in SK (period I)



^{8}B flux : $2.35 \pm 0.02 \pm 0.08$ [x 10^{6} /cm^{2}/sec]

$$\frac{\text{Data}}{\text{SSM(BP2004)}} = 0.406 \pm 0.004 ^{+0.014}_{-0.013}$$

Daily Variation of SK Rate

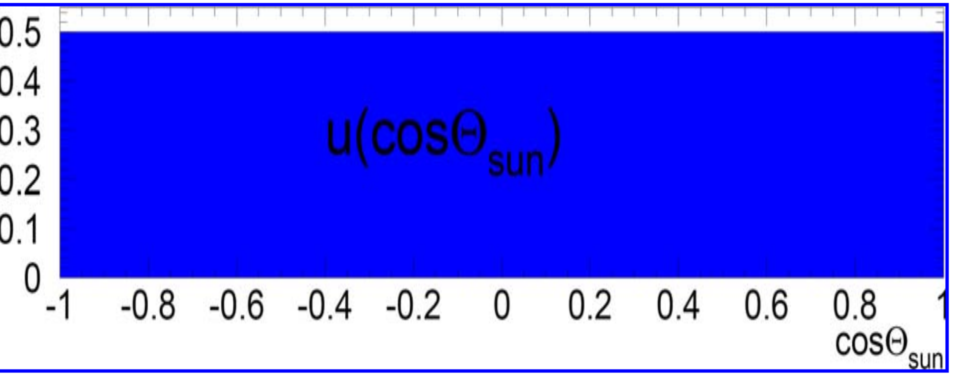


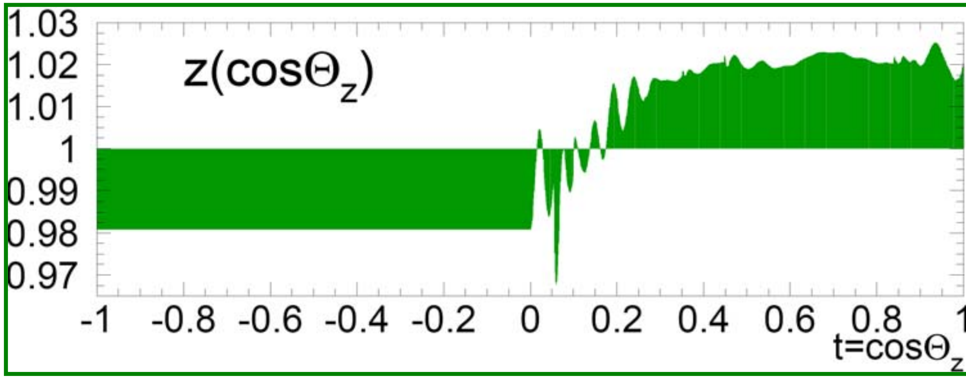
Unbined day/night analysis

search for energy and solar zenith angle variations, while employing the solar zenith angle as the time variable

Background — Signal (scaled by MC with mixing)

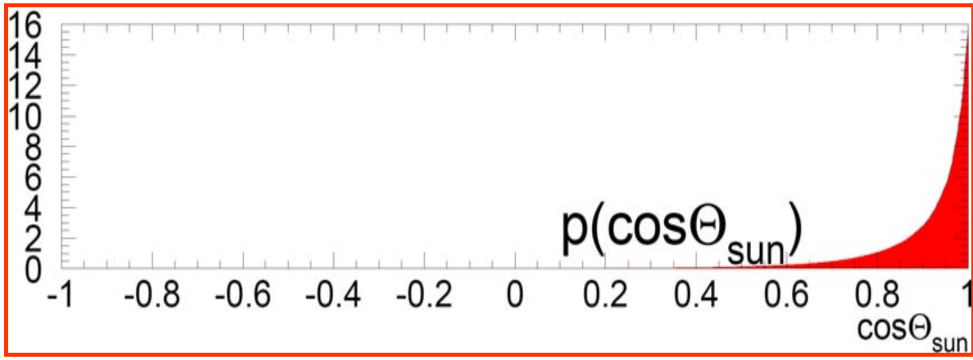
$$\mathcal{L} = e^{-\left(\sum_i B_i + S\right)} \prod_{i=1}^{N_{bin}} \prod_{\nu=1}^{n_i} \left(B_i \cdot u_i(c_\nu) + m_i S \cdot p(c_\nu, E_\nu) \times z_i(t_\nu) \right)$$





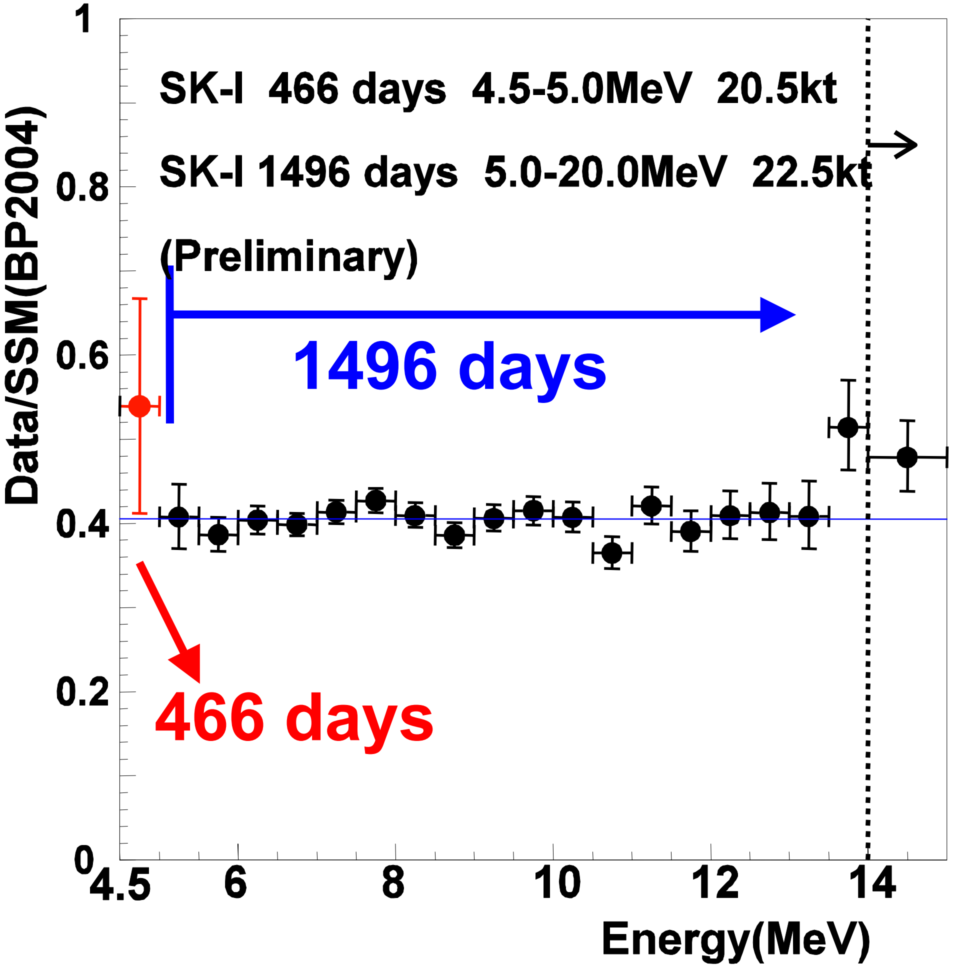
A_{DN}=-1.8±1.6$^{+1.3}_{-1.2}$%

Old: A_{DN}=-2.1±2.0$^{+1.3}_{-1.2}$%



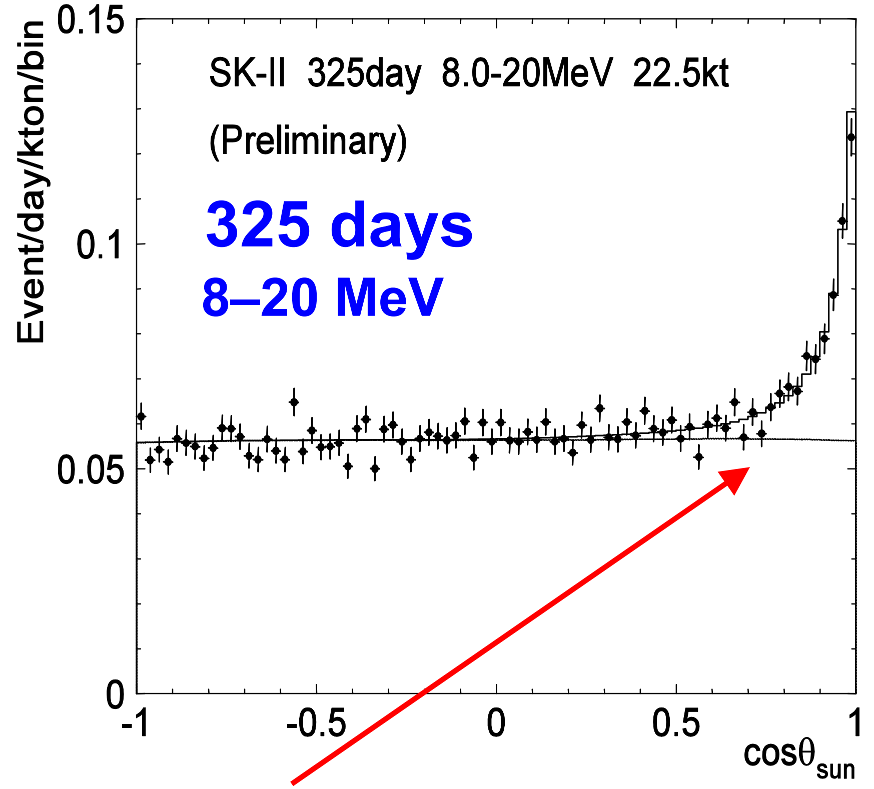
Preliminary: SKI (low E) and SKII (new)

Solar neutrino energy spectrum



Direction to the sun

Dec.24,2002 – March 25, 2004



Flux=2.38±0.09 (stat.) [x10^6/cm^2/s]

Source: Neutrino 2004

Preliminary data consistent with previous results

Sudbury Neutrino Observatory (Canada)

2092 m to Surface (6010 m w.e.)

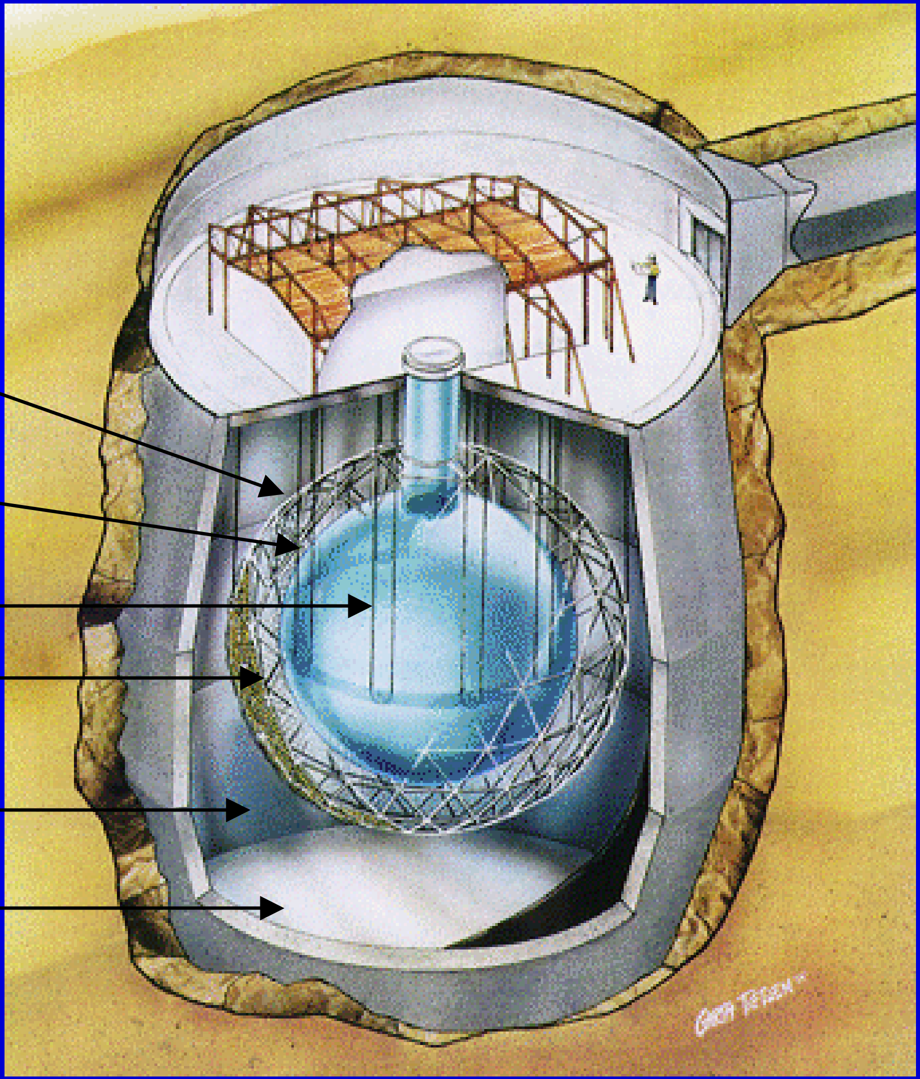
PMT Support Structure, 17.8 m
9456 20 cm PMTs
~55% coverage within 7 m

Acrylic Vessel, 12 m diameter

1000 tonnes D_2O
1700 tonnes H_2O, Inner Shield

5300 tonnes H_2O, Outer Shield
Urylon Liner and Radon Seal

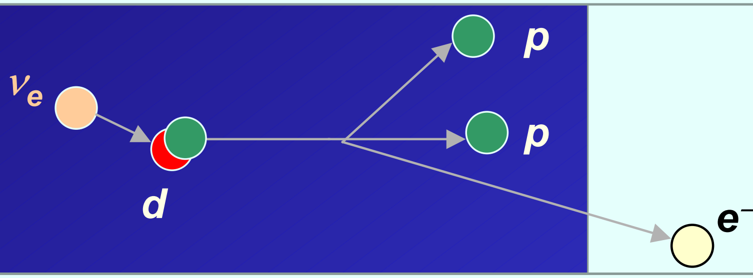
Energy Threshold = 5.511 MeV



The SNO detector observes the following interactions:

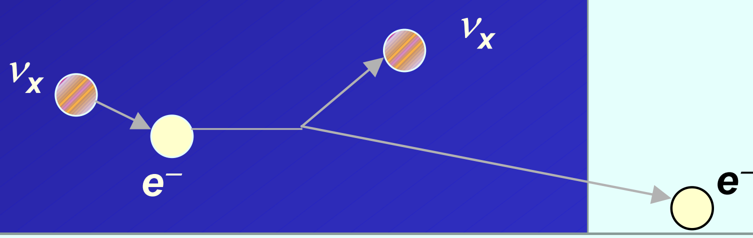
CC Charged Current

$$\nu_e + d \rightarrow p + p + e^-$$



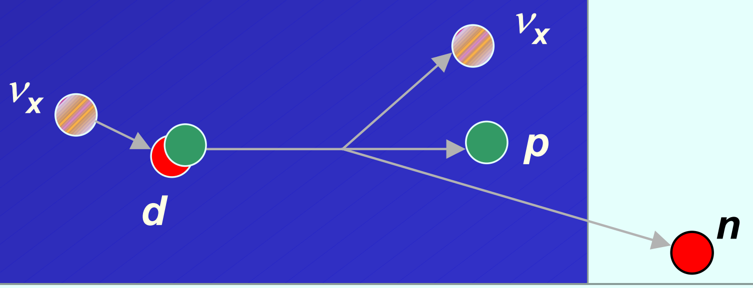
ES Elastic Scattering

$$\nu_x + e^- \rightarrow \nu_x + e^-$$



NC Neutral Current

$$\nu_x + d \rightarrow \nu_x + p + n$$



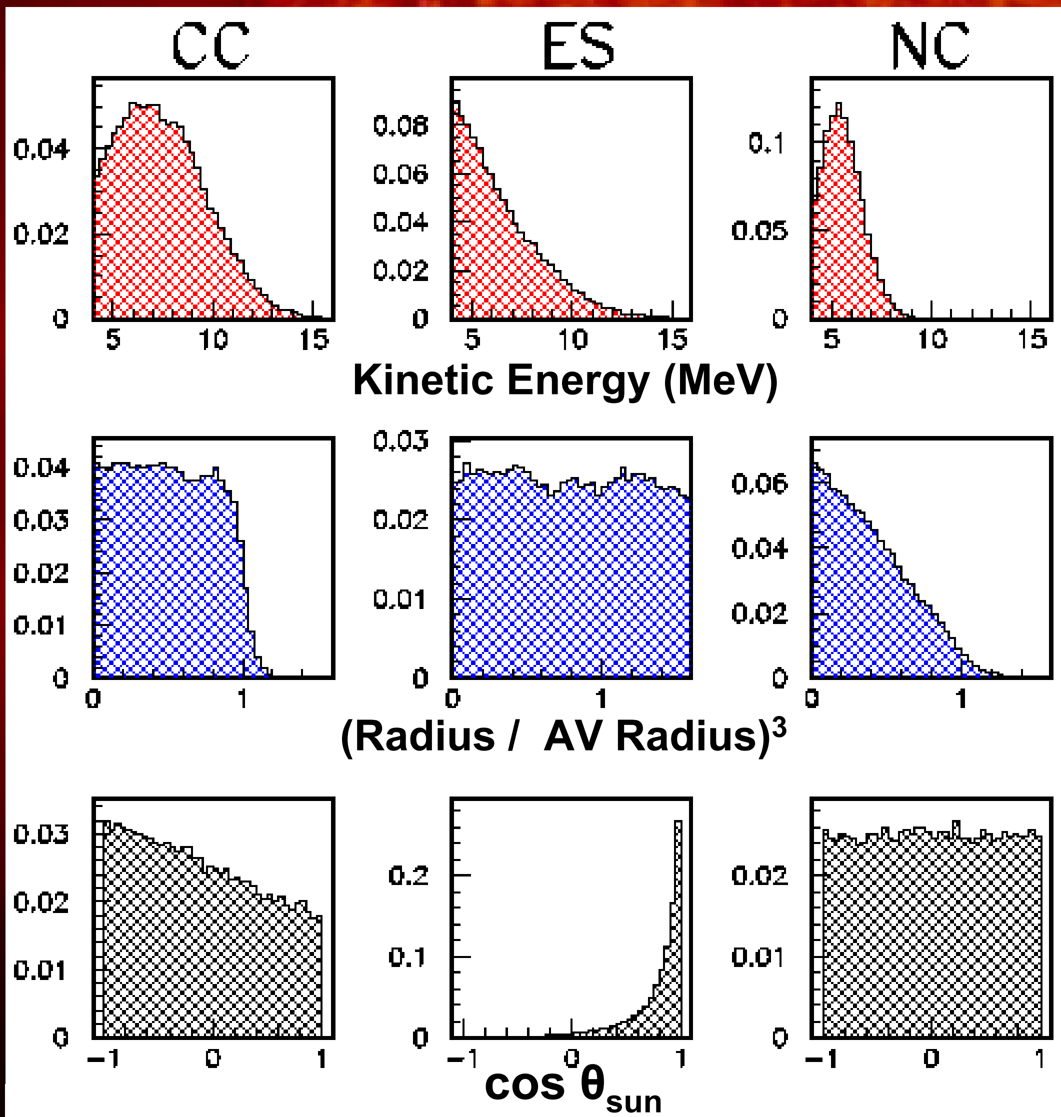
$x = e, \mu, \tau$

Detected Particle

Subury Neutrino Observatory

D_2O Results (2002)

The limitation and weakness ?!?!



Used the energy PDF to statistically discriminate CC, ES, and NC

Assume and undistorded energy spectrum

In other words, a FLAT survival probability!!!

Shape Constrained Neutrino Fluxes (D_2O)

Signal Extraction in Φ_{CC}, Φ_{NC}, Φ_{ES} with $E_{Theshold}$ > 5 MeV

$$\Phi_{cc}(\nu_e) = 1.76^{+0.06}_{-0.05}\,(\text{stat.})^{+0.09}_{-0.09}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{es}(\nu_x) = 2.39^{+0.24}_{-0.23}\,(\text{stat.})^{+0.12}_{-0.12}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{nc}(\nu_x) = 5.09^{+0.44}_{-0.43}\,(\text{stat.})^{+0.46}_{-0.43}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

Signal Extraction in Φ_e, $\Phi_{\mu\tau}$

$$\Phi_e = 1.76^{+0.05}_{-0.05}\,(\text{stat.})^{+0.09}_{-0.09}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}\,(\text{stat.})^{+0.48}_{-0.45}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

Subury Neutrino Observatory

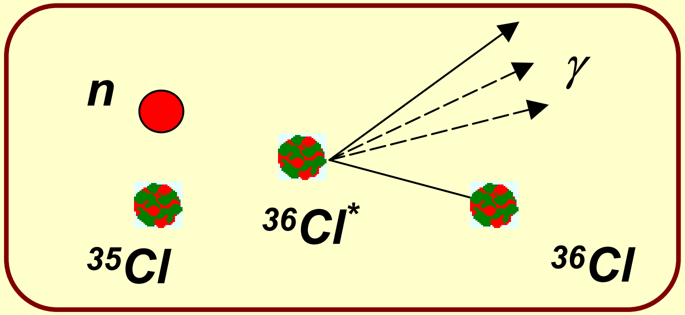
Salt Results (391 days)

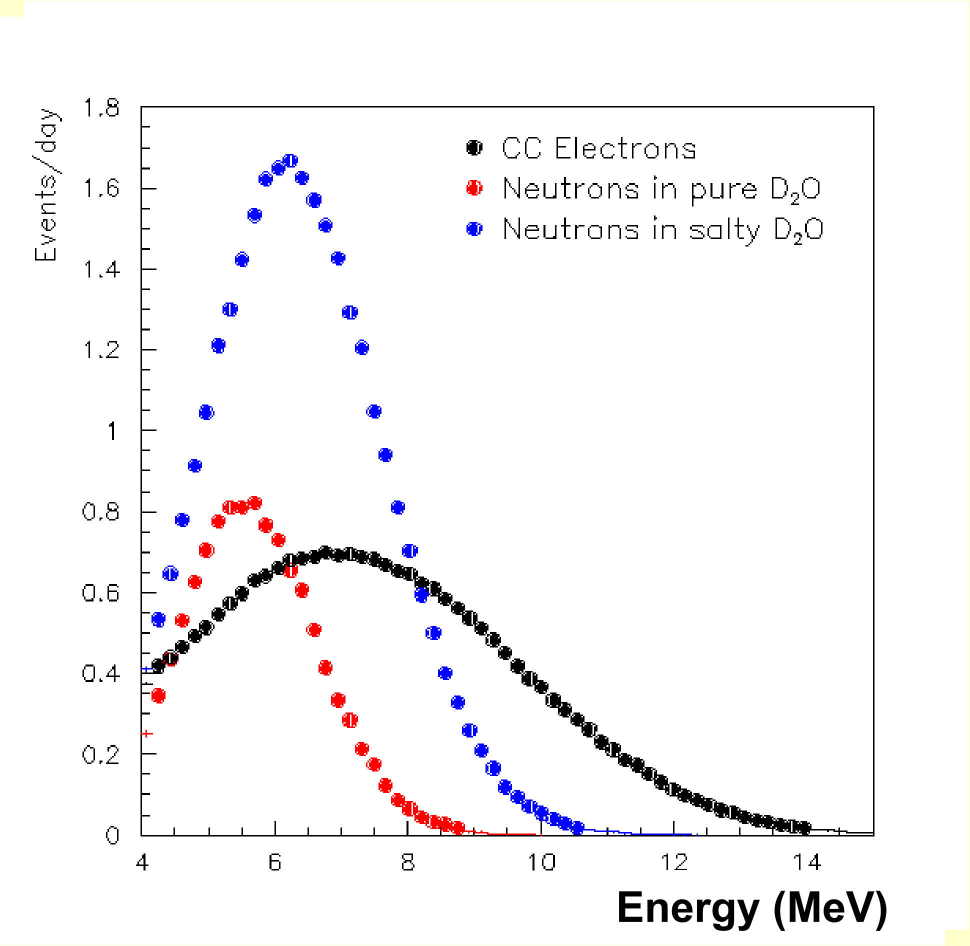
NEW

Nucl-exp / 0502021

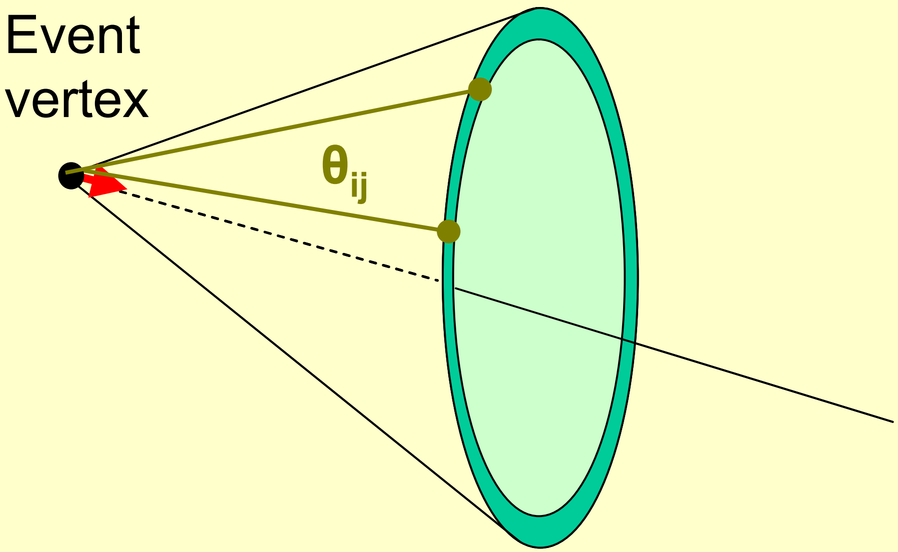
Advantages of Salt: more sensitive

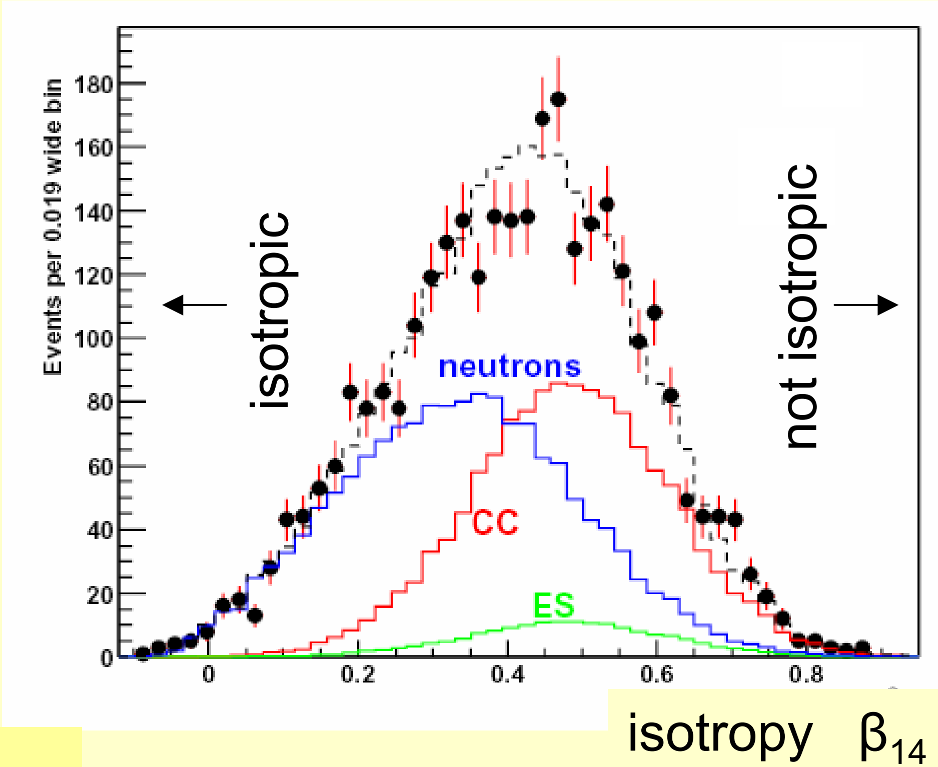
- Neutrons capturing on ^{35}Cl provide higher neutron energy above threshold.
- Higher capture efficiency
- Gamma cascade changes the angular profile.





Advantages of salt: event isotropy



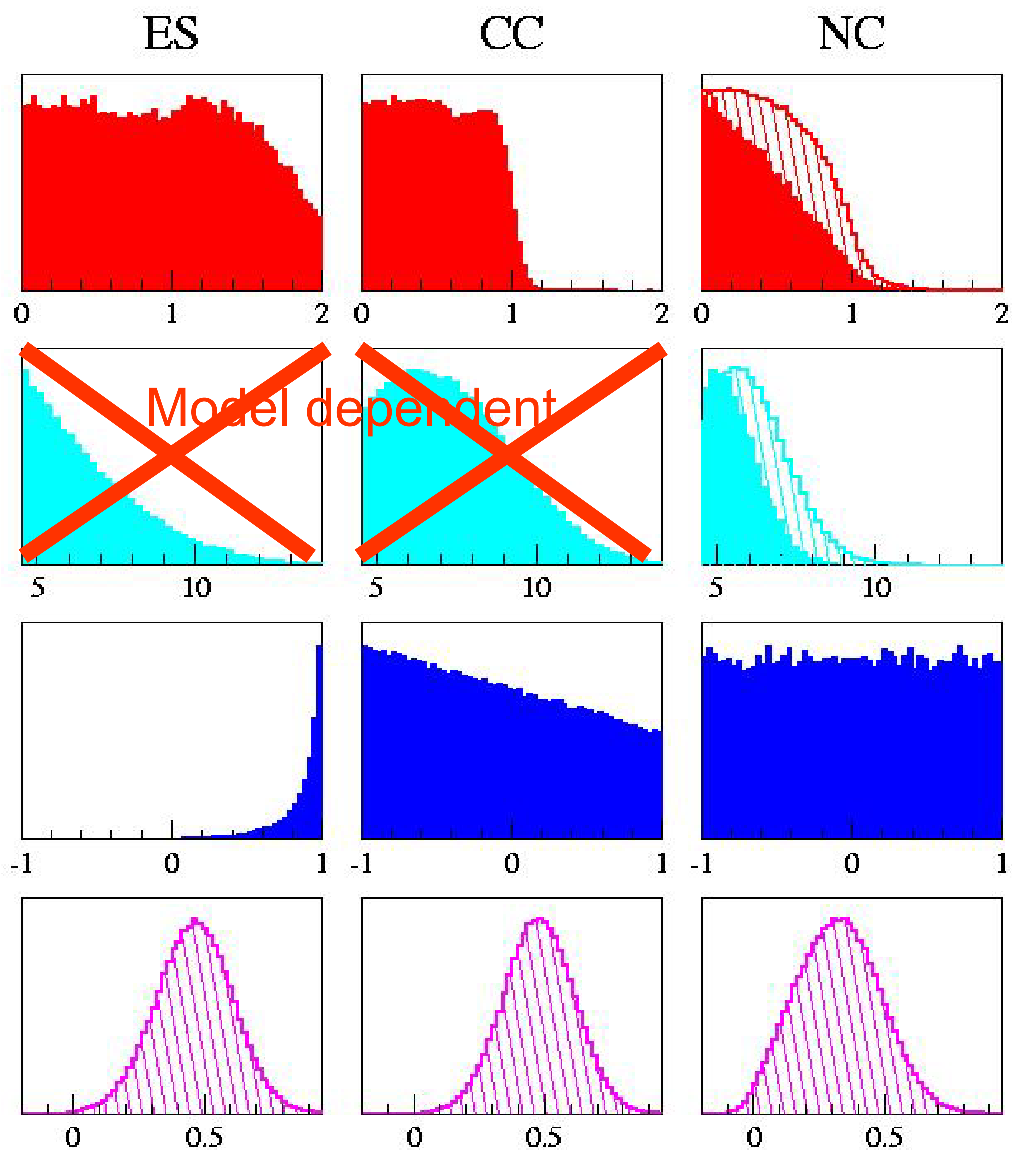


Isotropy variable, β_{14} , function of angles between each pair of hit PMTs (**θ_{ij}**) in event [similar to *thrust* in collider physics]

β_{14} powerful discriminating variable between NC and CC/ES events

Salt phase (July 2001 – September 2003)

$$n + {}^{35}\text{Cl} \rightarrow {}^{36}\text{Cl}^* \rightarrow {}^{36}\text{Cl} + \gamma' s \quad : \; \text{E} = 8.6\ \text{MeV}, \sigma_{n,\gamma} = 44b$$



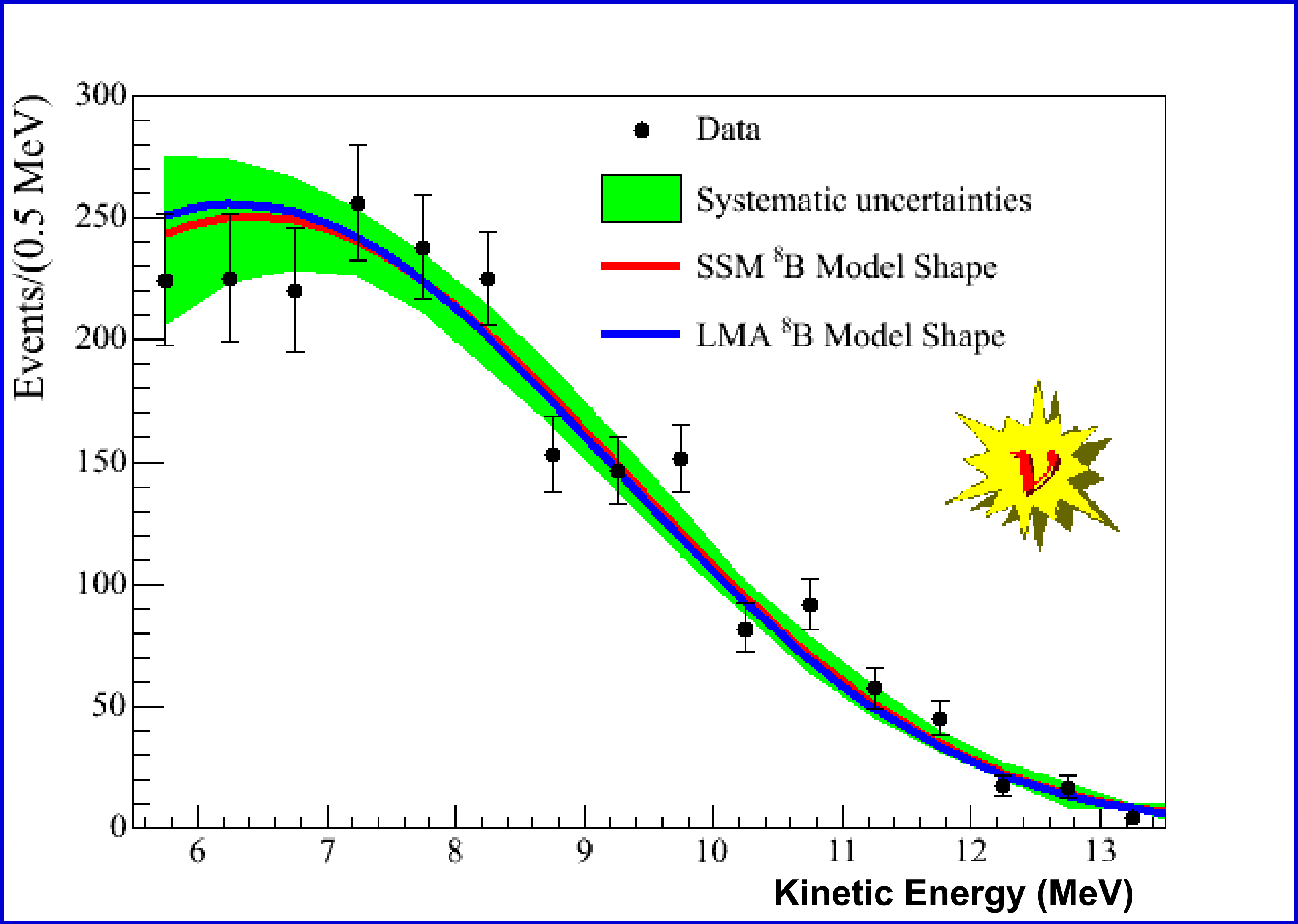
Radial Distribution (R^3, R_{AV}=1) ← NC changed due to larger $\sigma_{n\gamma}$

Energy Distribution (MeV) ← NC shifted to higher energy

Solar Direction Distribution ← Unchanged

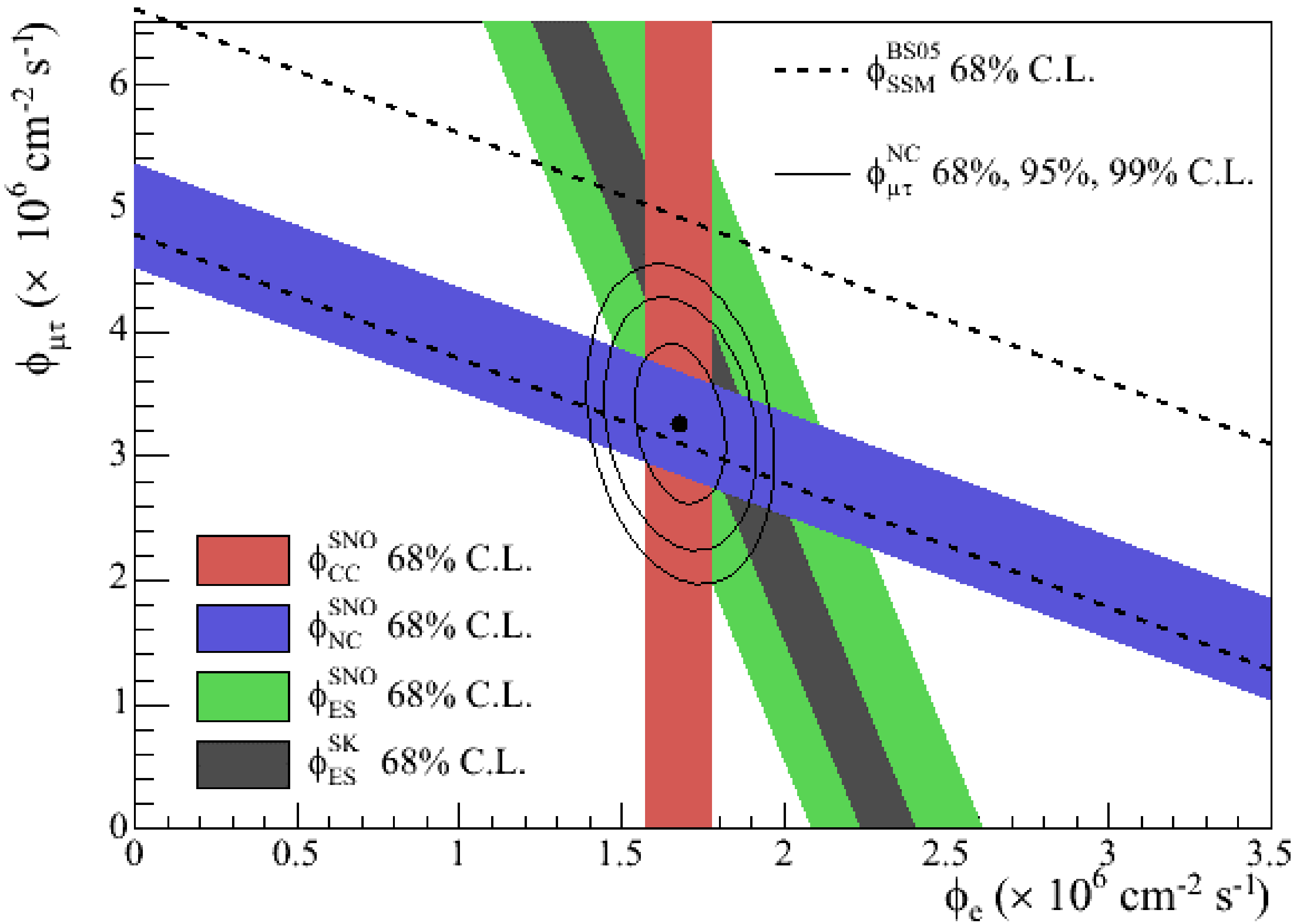
Isotropy Distribution ← All new due to multiple γ's

Charged Current ($CC=\nu_e$) Spectrum



SNO: Salt results and comparison to SSM

More precise salt results confirm D_2O results



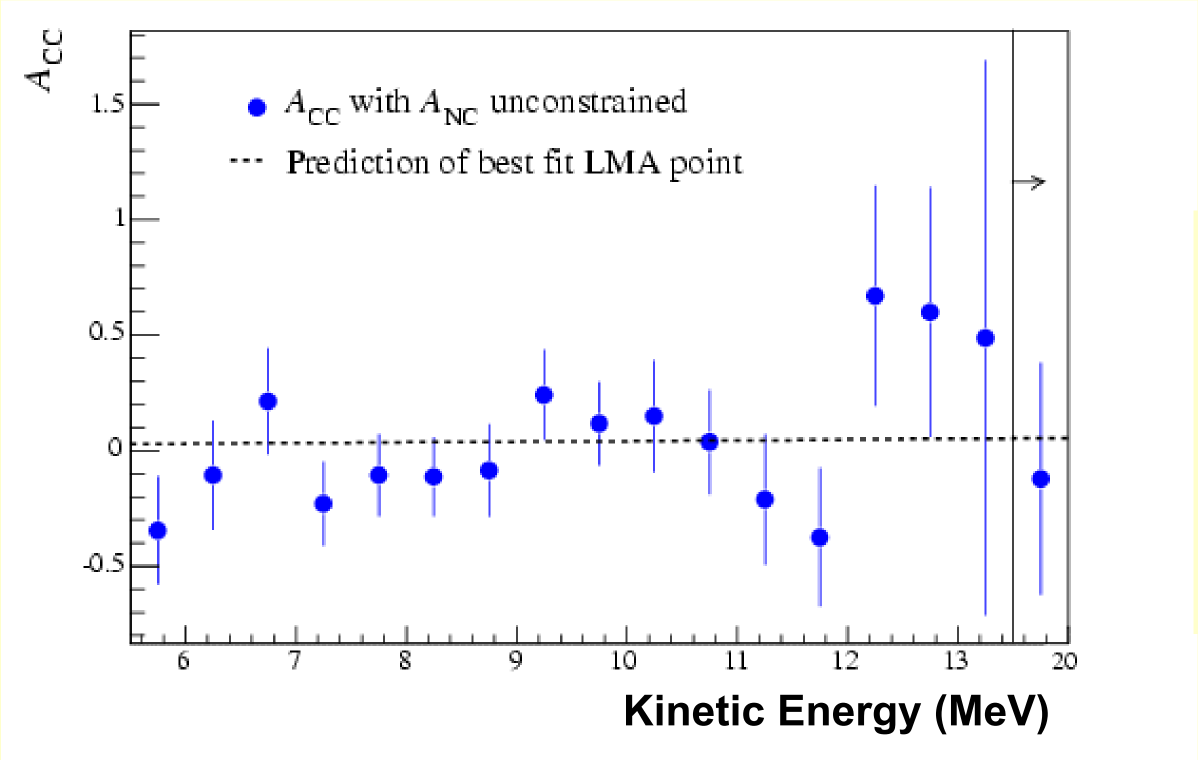
Day/Night Asymmetries

$$A_X = \frac{(\Phi_{night} - \Phi_{day})}{(\Phi_{night} + \Phi_{day})/2}$$

A_{CC}= -0.056 ± 0.074 (stat.) ± 0.051 (syst.)

A_{NC}= 0.042 ± 0.086(stat.) ± 0.067 (syst.)

A_{ES}= 0.146 ± 0.198(stat.) ± 0.032 (syst.)



A_{CC} and A_{NC} are correlated (ρ = -0.532)

In standard neutrino oscillations, A_{NC} should be zero…

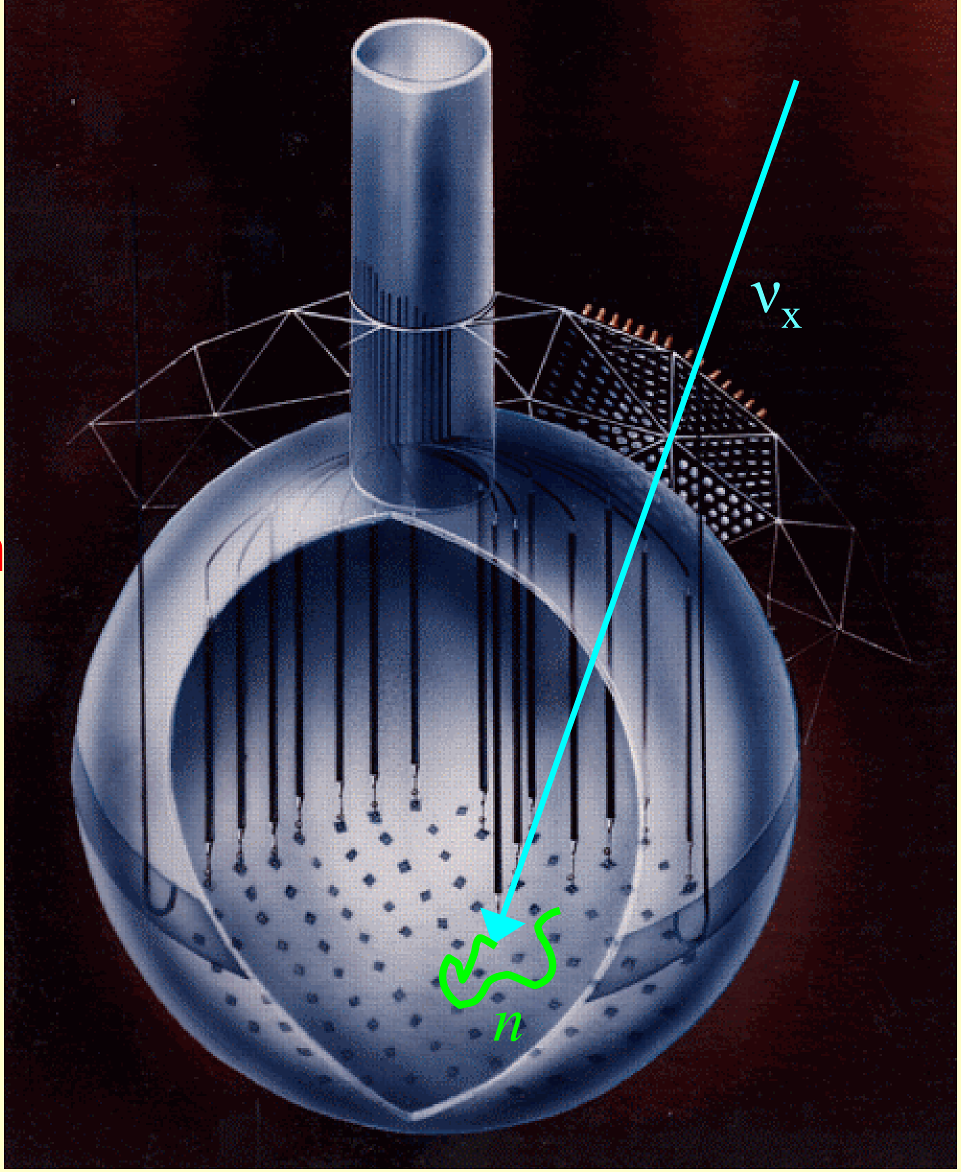
SNO at Present

NC $\nu_x + d \rightarrow p + n + \nu_x$

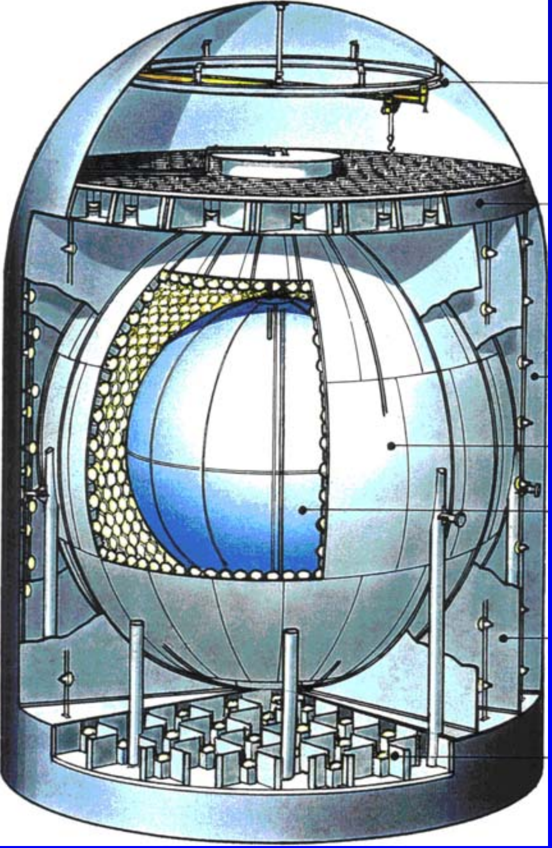
$$n + {}^3He \rightarrow p + t$$

- Event by event separation
- Break the correlation between NC & CC events
- Measure in separate data streams NC & CC events
- Different systematic errors than neutron capture on NaCl
- Taking data until end of 2006

Neutral Current Detectors



KamLAND: Neutrinos Produced at Reactors



KamLAND

- **1000 tons liquid scintillator**
- **13 m thin transparent balloon**
- **1325 inner looking PMT's**

Powerful (70 GW) reactors at L ~ 180 ± 35 km
Produce 1.3 x 10^6 $\bar{\nu}_e$/s/cm^2
Target ~ 10^{32} protons
Fully covers LMA (in coincidence mode)

Antineutrinos detected through inverse *b*-decay: $\bar{\nu}_e + p \rightarrow e^+ + n$

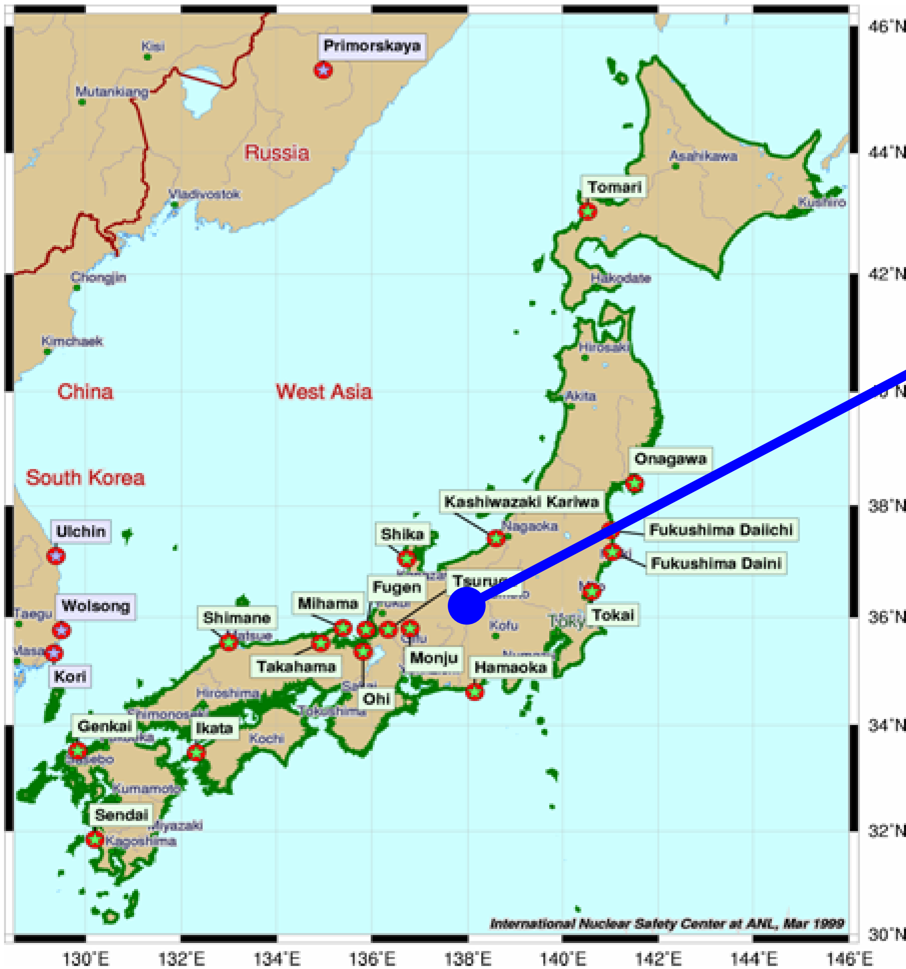
Energy threshold: 1.8 MeV

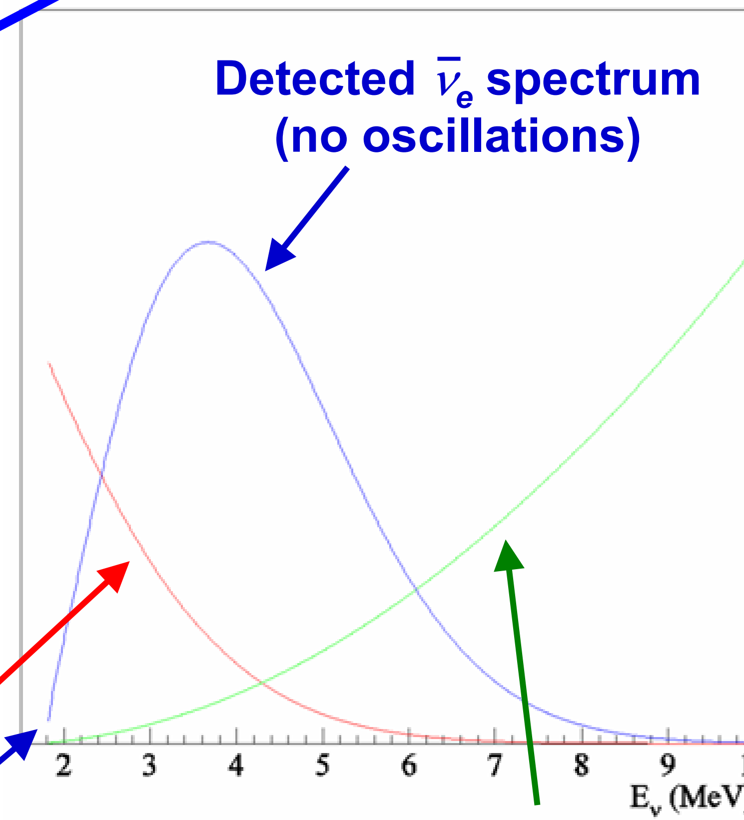
Prompt signal: $e^+ e^- \rightarrow 2\gamma$ (0.51 MeV) with $E_{\text{prompt}} = E_{\bar{\nu}} - 0.8$ MeV

Delayed signal (~200 μs): neutron capture on hydrogen $E_{\text{delay}} = 2.2$ MeV

Reactors Antineutrinos

KamLAND





Reactor $\bar{\nu}_e$ spectrum

1.8 MeV threshold

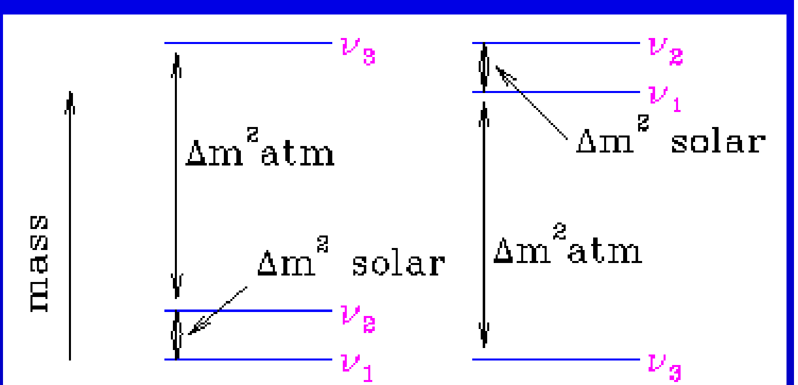
Inverse β-decay cross-section

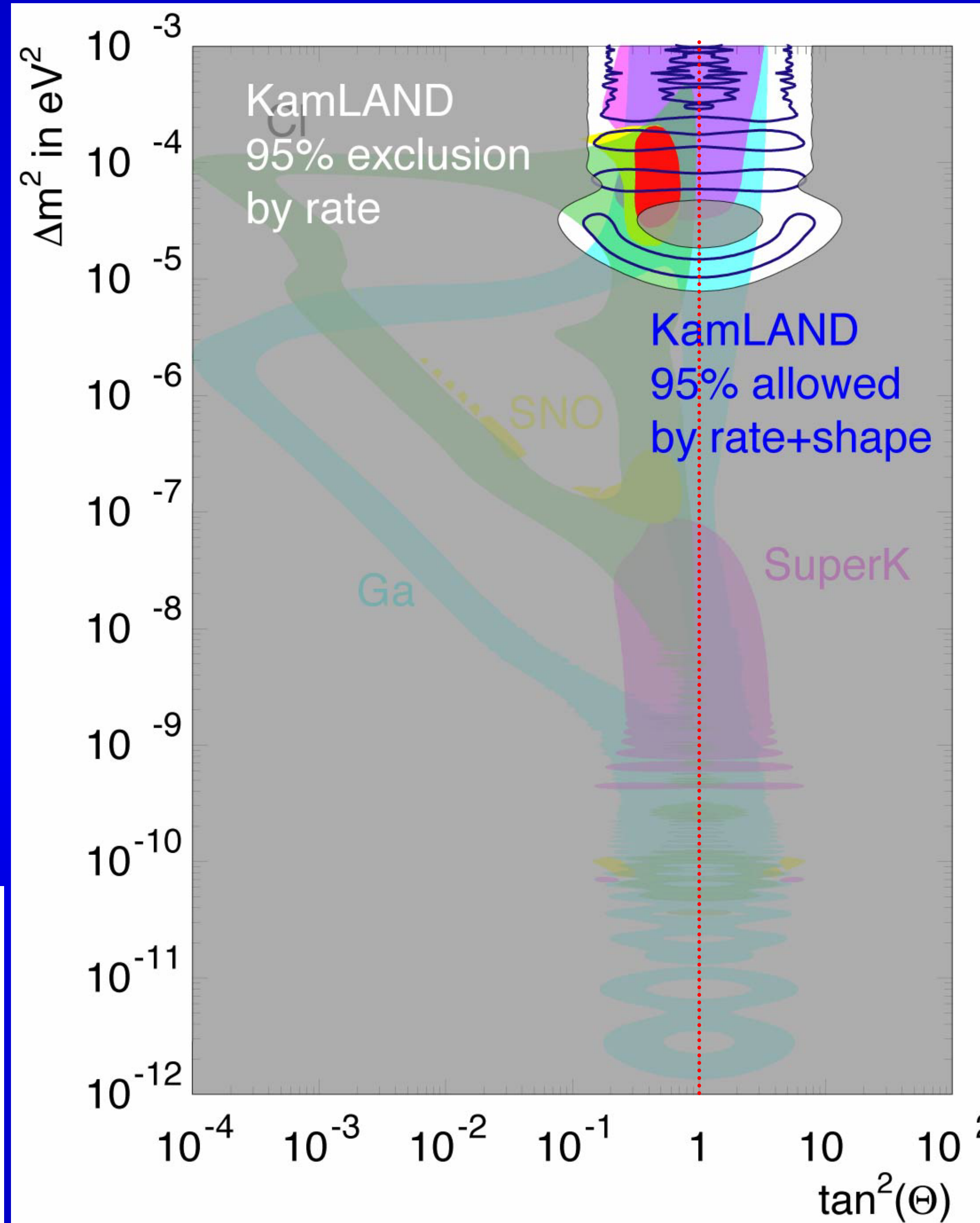
Progress in 2002 on the Solar Neutrino Problem

March 2002

April 2002 with SNO (confirm with salt in 2005)

Dec 2002 with KamLAND



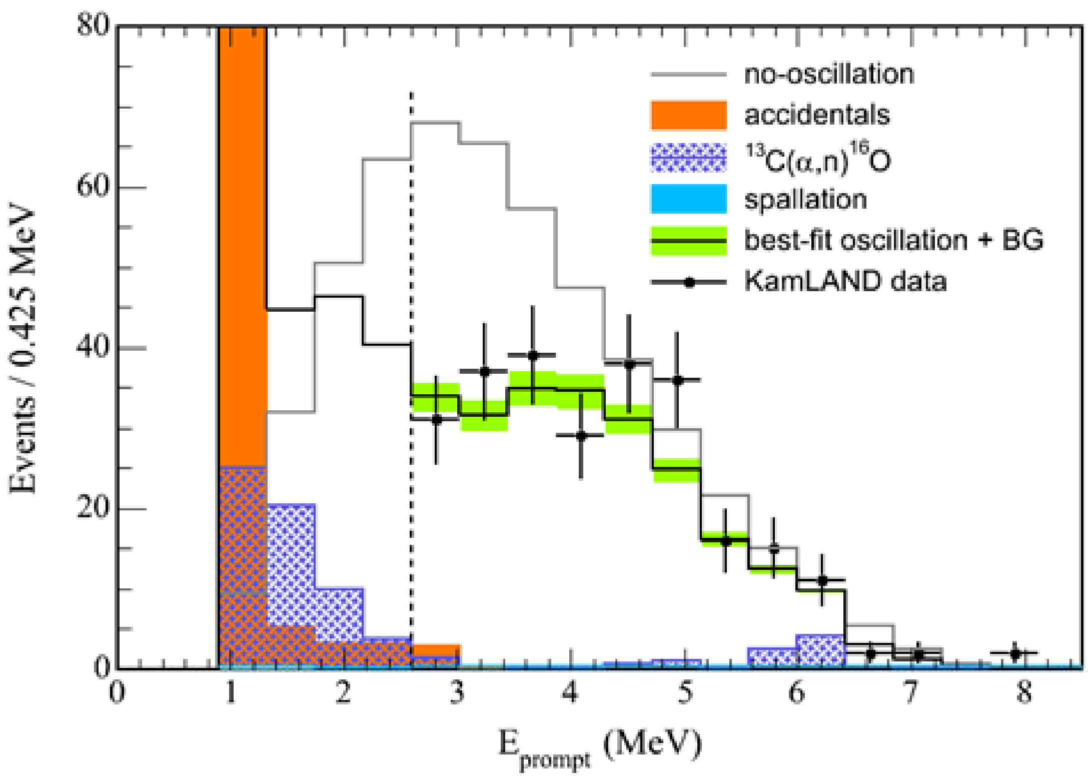


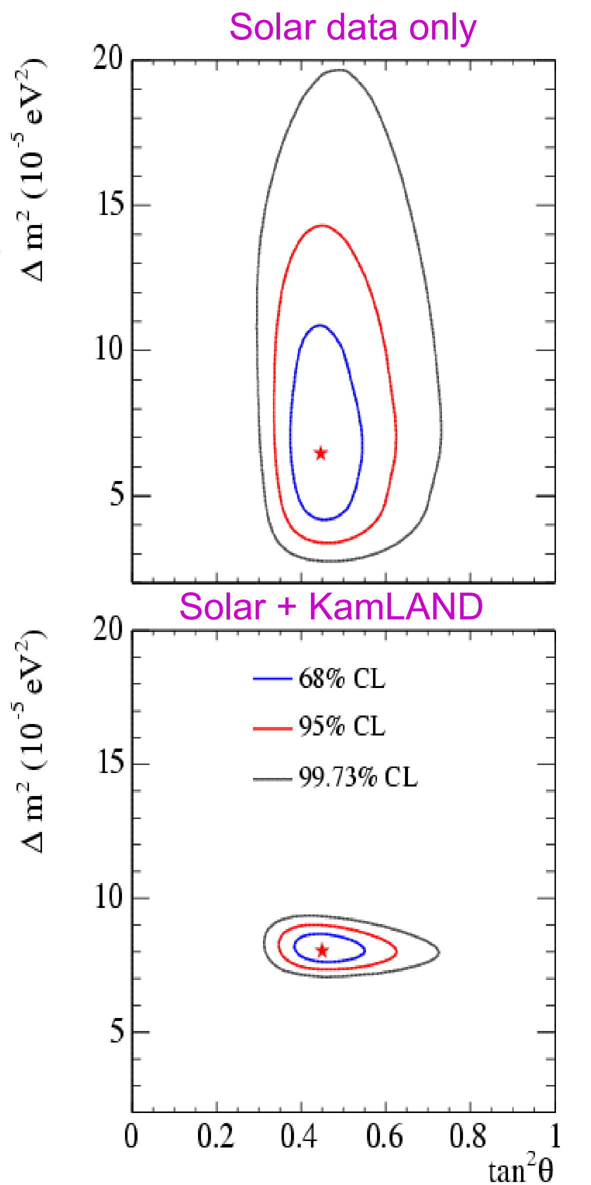
Latest KamLAND Result (Nov 2004)

Statistical significance of disappearance: 99.998% (was 99.95%)
Confirm shape distortion at 99.6% C.L.

Solar + KamLAND (best fit)

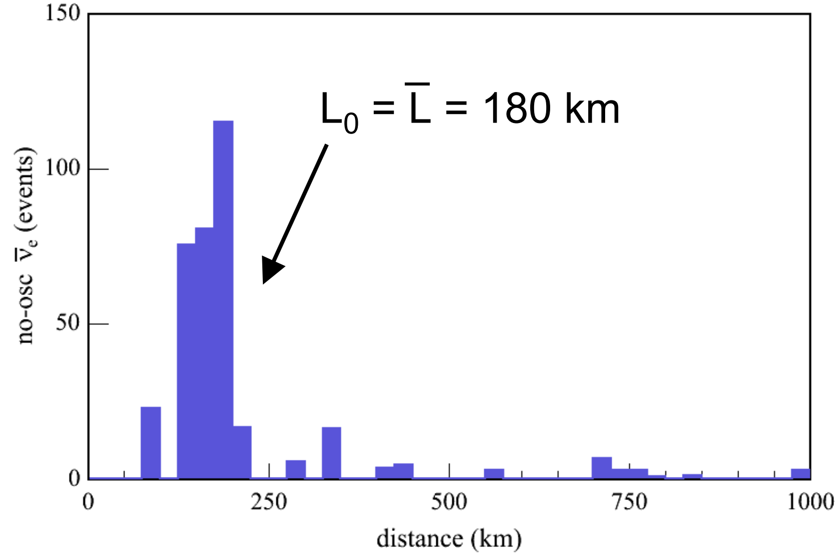
$\Delta m^2 = 8.0^{+0.6}_{-0.4} \times 10^{-5}\ eV^2 \quad \theta = 33.9^{+2.4}_{-2.2}$ degrees





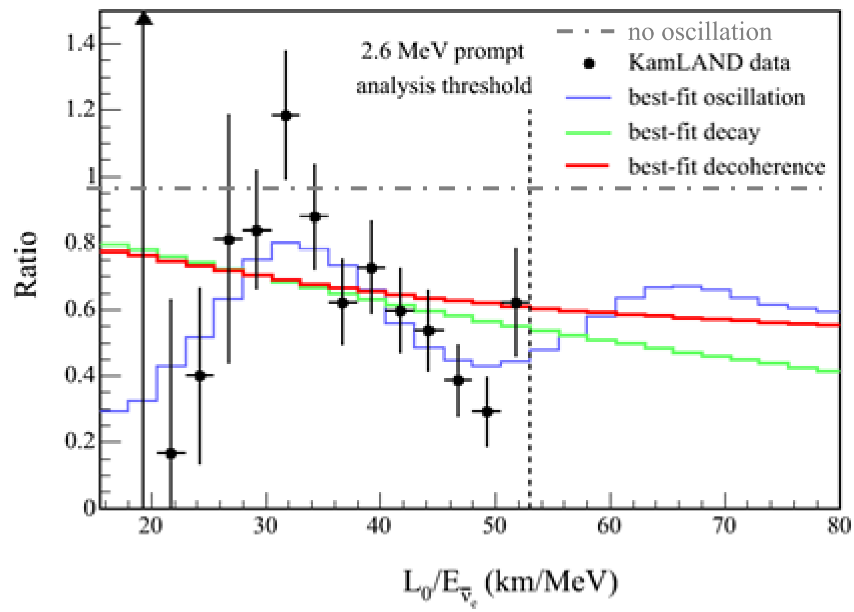
KamLAND: L/E Analysis

KamLAND uses a range of distances (L)
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 isolates the oscillation (sine) pattern



Goodness of fit:

0.7% - decay
1.8% - decoherence
11.1% - oscillation
0.4% - constant suppression



Data prefer oscillation to alternate hypotheses

References:

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

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

Atmospheric Neutrinos

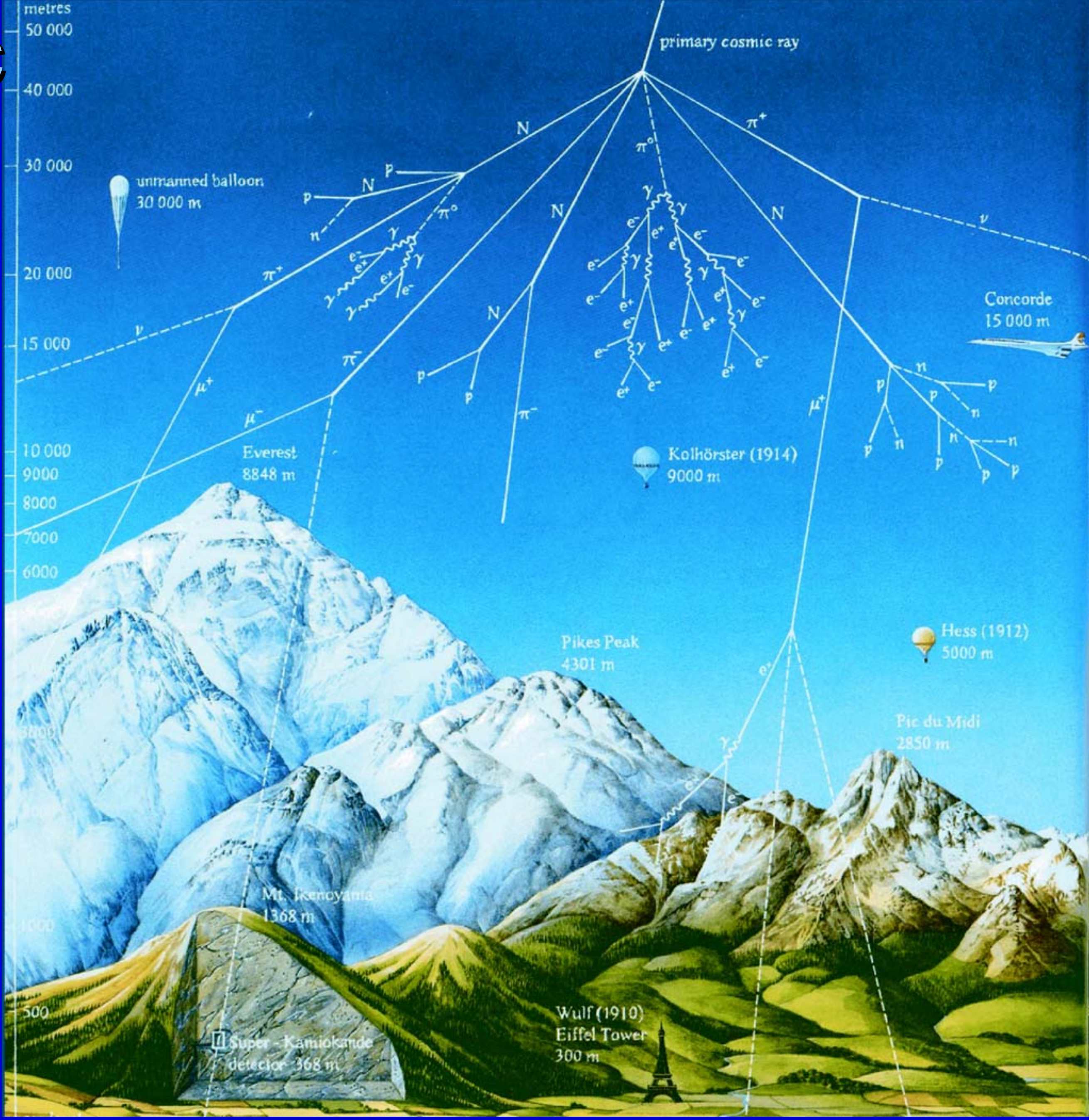
SuperK

- Zenith angle results (SKI)

  hep-ex/0501064 NEW

- L/E analysis with SKI

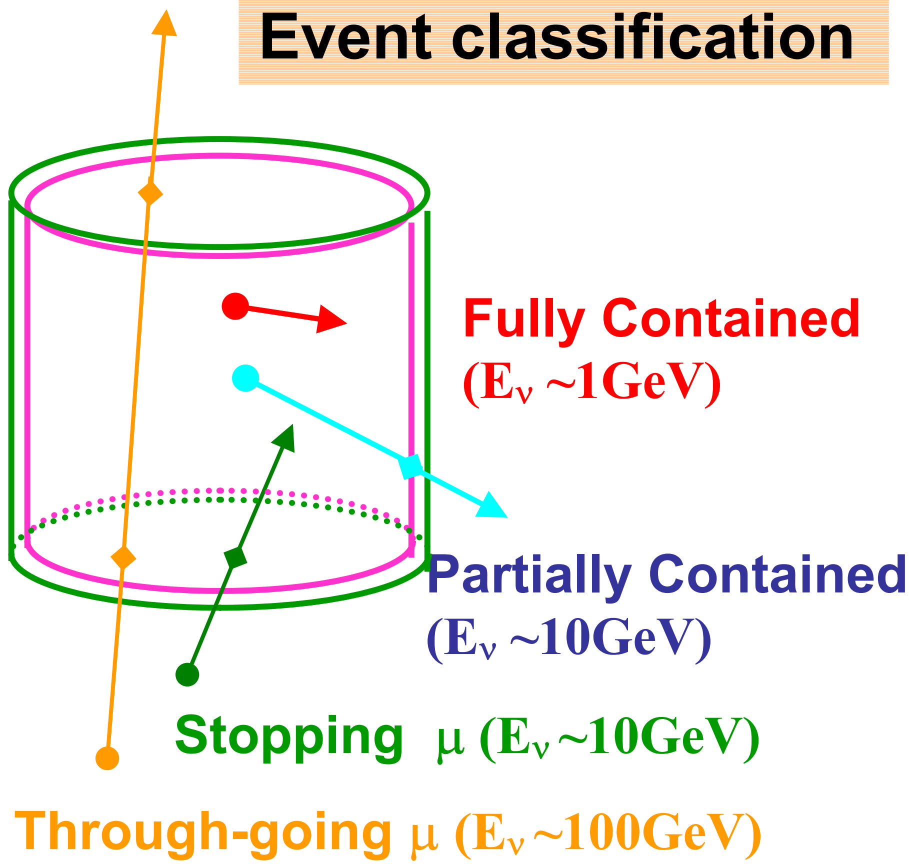
- Status SKII



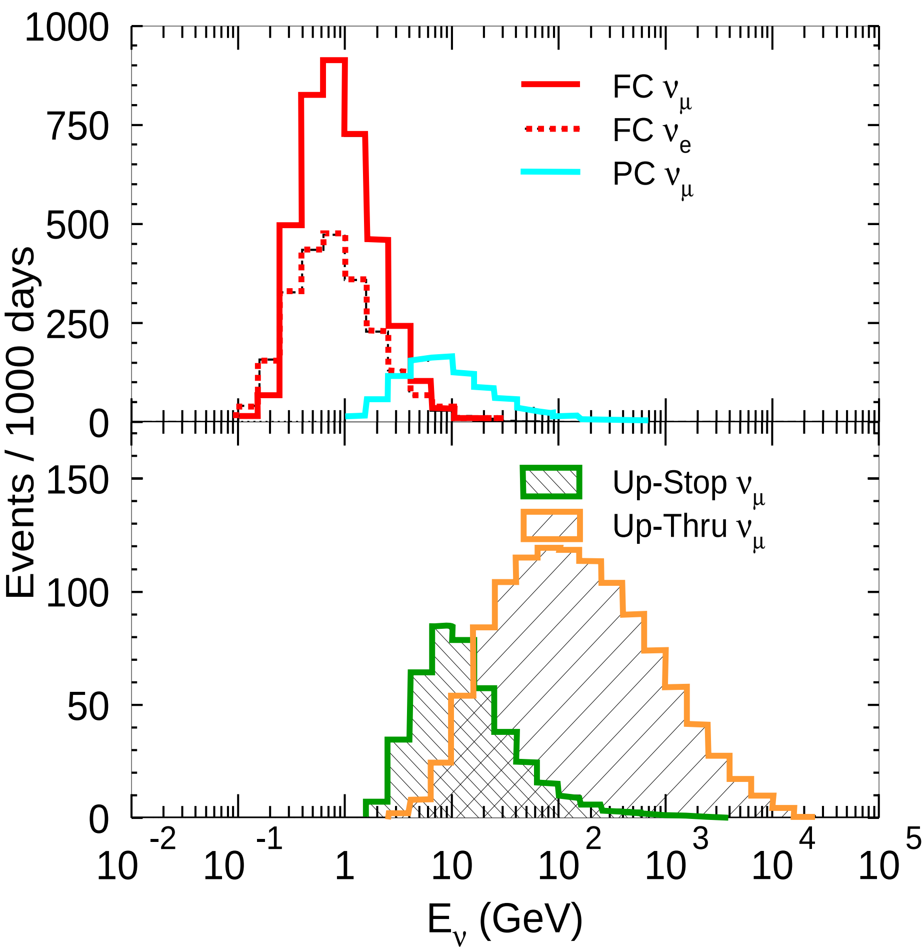
SuperK: Atmospheric Neutrinos

SK1 data set: (FC,PC 1489days, up-μ 1646 days)

Event classification



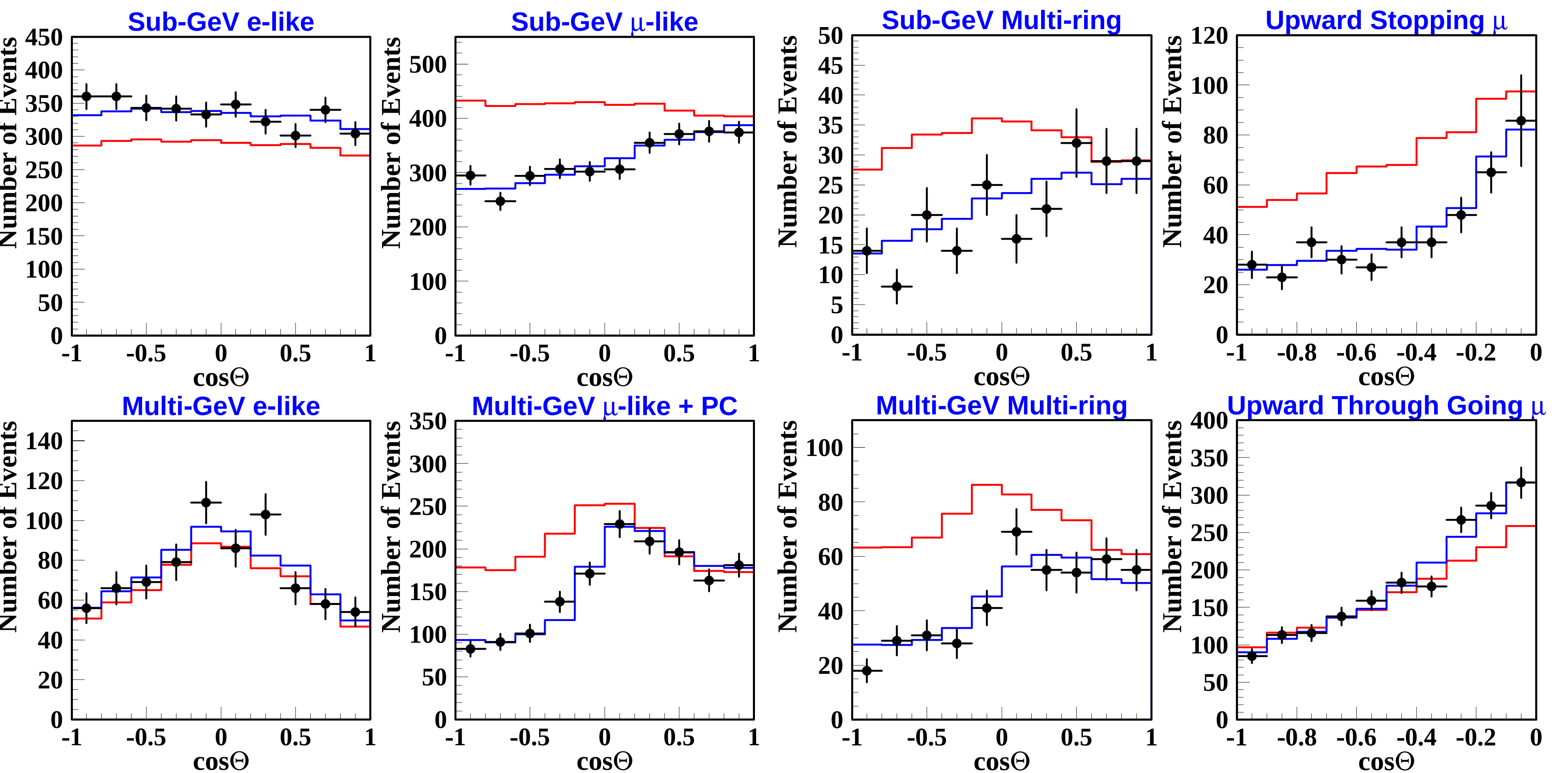
ν energy distribution



Zenith Angle Distributions (SKI re-analyzed)

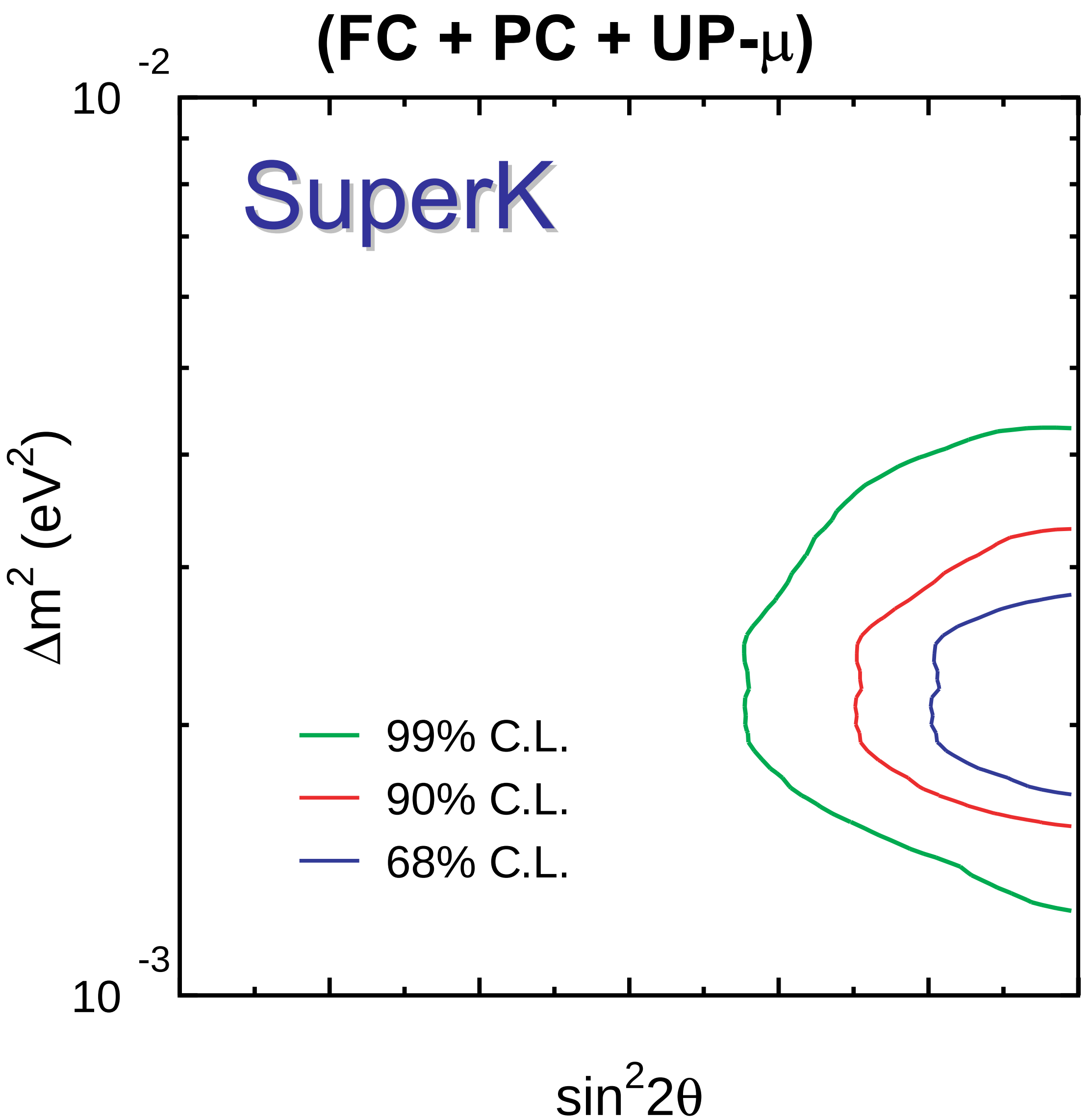
$\nu_\mu \leftrightarrow \nu_\tau$
2-flavor oscillations

Best fit
$\sin^2 2\theta=1.0$, $\Delta m^2=2.1\times10^{-3}$ eV^2
Null oscillation



Source: ICHEP 2004

2-flavor $\nu_\mu \leftrightarrow \nu_\tau$ Oscillation Analysis: Results



Best fit:

$\sin^2 2\theta = 1.0$

$\Delta m^2 = 2.1\times10^{-3}$ eV^2

$\chi^2 = 174.8/177$ d.o.f.

90% C.L. region:

$\sin^2 2\theta > 0.92$

$1.5 < \Delta m^2 < 3.4\times10^{-3}$ Ev^2

Unphysical

$\sin^2 2\theta = 1.02$

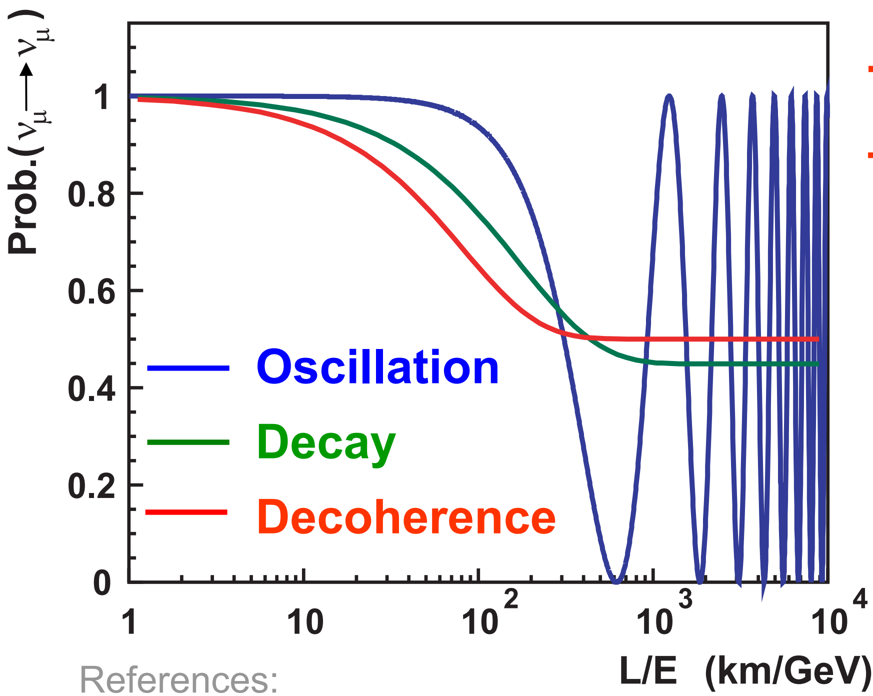
$\Delta m^2 = 2.1\times10^{-3}$ eV^2

$\chi^2 = 174.5/177$ d.o.f.

L/E Analysis SuperK

$P_{\mu\tau} = \sin^2(2\theta)\,\sin^2(1.27\Delta m^2\, L / E)$

Search the first dip of the sinusoidal $\upsilon_\mu \leftrightarrow \upsilon_\tau$ flavor transition



→ Direct evidence for oscillations

→ Strong constraint to oscillation parameters, especially Δm^2 value

Selection Criteria

- Expand fiducial volume (FC)
  - need more statistics
- Select events with high resolution in L/E
  - $\Delta L/E < 70\%$

  Use FC(single, multi-ring) μ-like and PC

References:

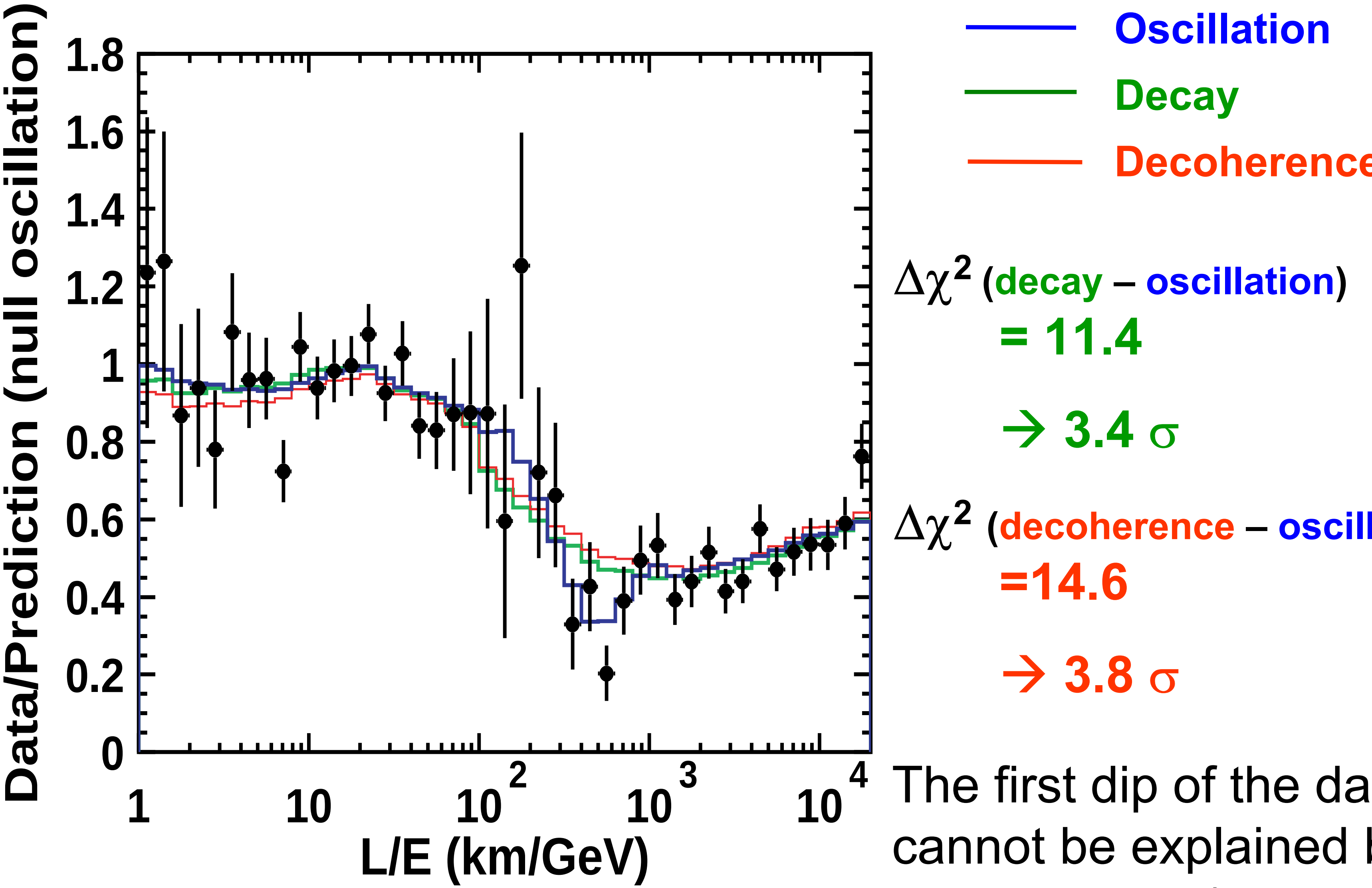
Barger et al: PRD54 (1996) 1

Barger et al: PLB462 (1999) 462

Grossman and Worah: hep-ph/9807511

Lisi et al: PRL85 (2000) 1166

L/E significance

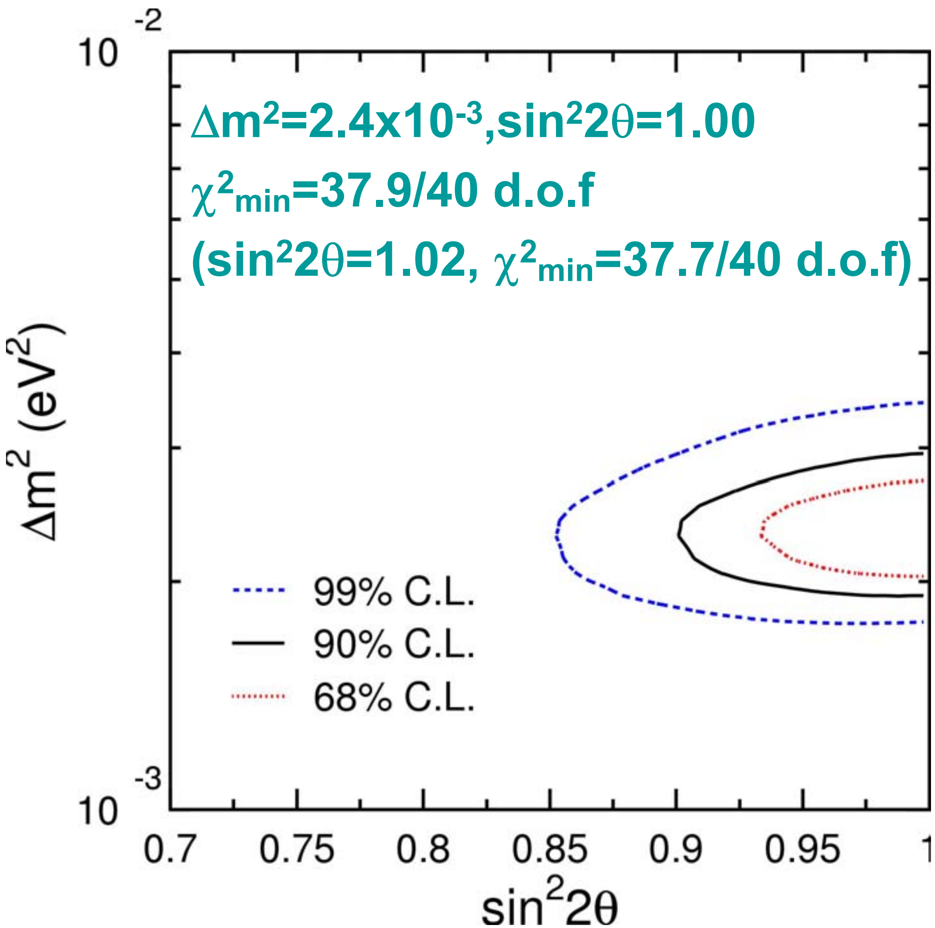


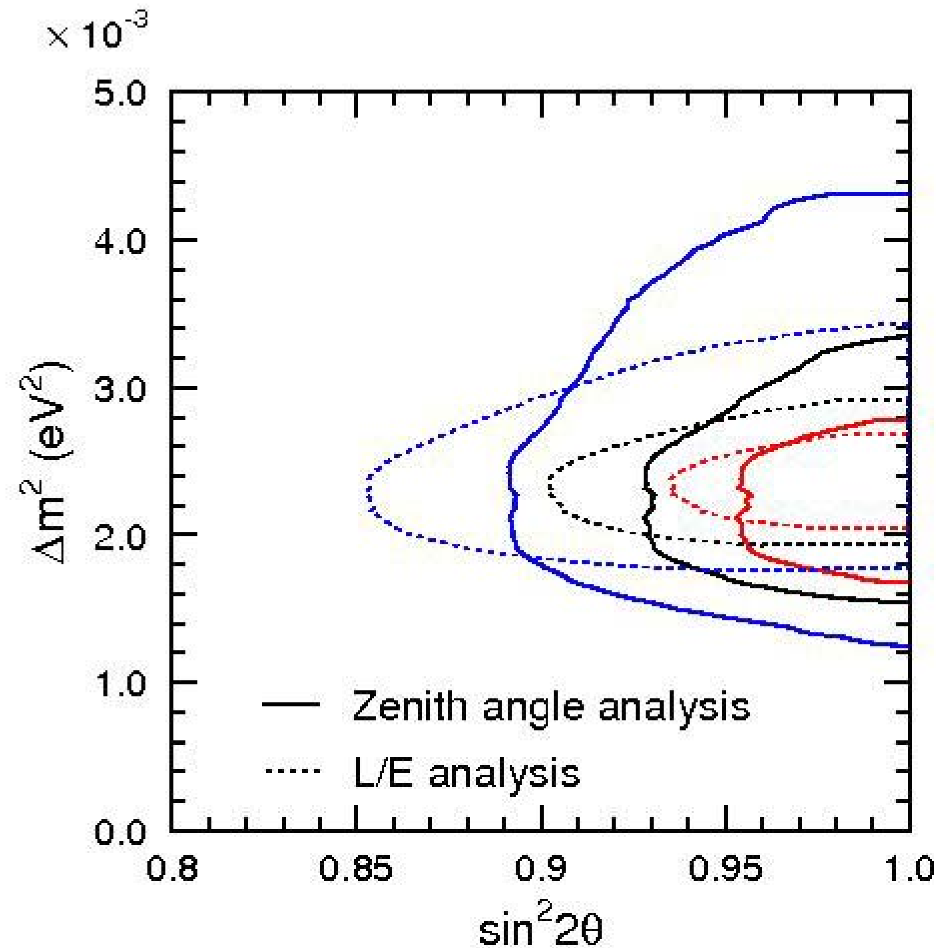
$\Delta\chi^2$ (decay – oscillation)
= 11.4
→ 3.4 σ

$\Delta\chi^2$ (decoherence – oscillation)
=14.6
→ 3.8 σ

The first dip of the data cannot be explained by other models (P ~ 0.1%)

L/E Oscillation Parameters





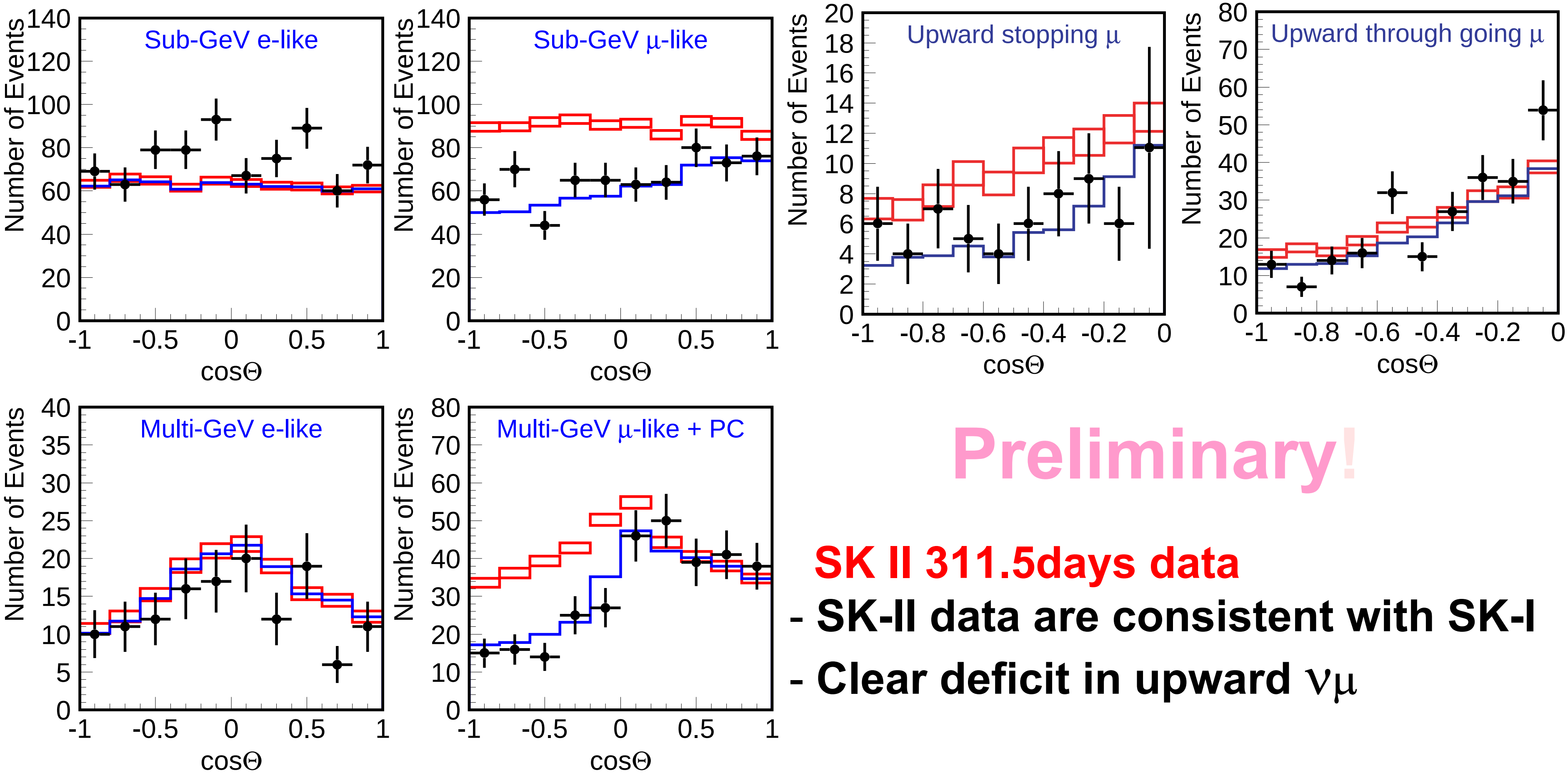
90% C.L. region:

$\sin^2 2\theta > 0.90$

$1.9 < \Delta m^2 < 3.0\times10^{-3}\ eV^2$

L/E
Strong constraint on Δm^2

Zenith Angle Distributions (SKII PRELIMINARY)



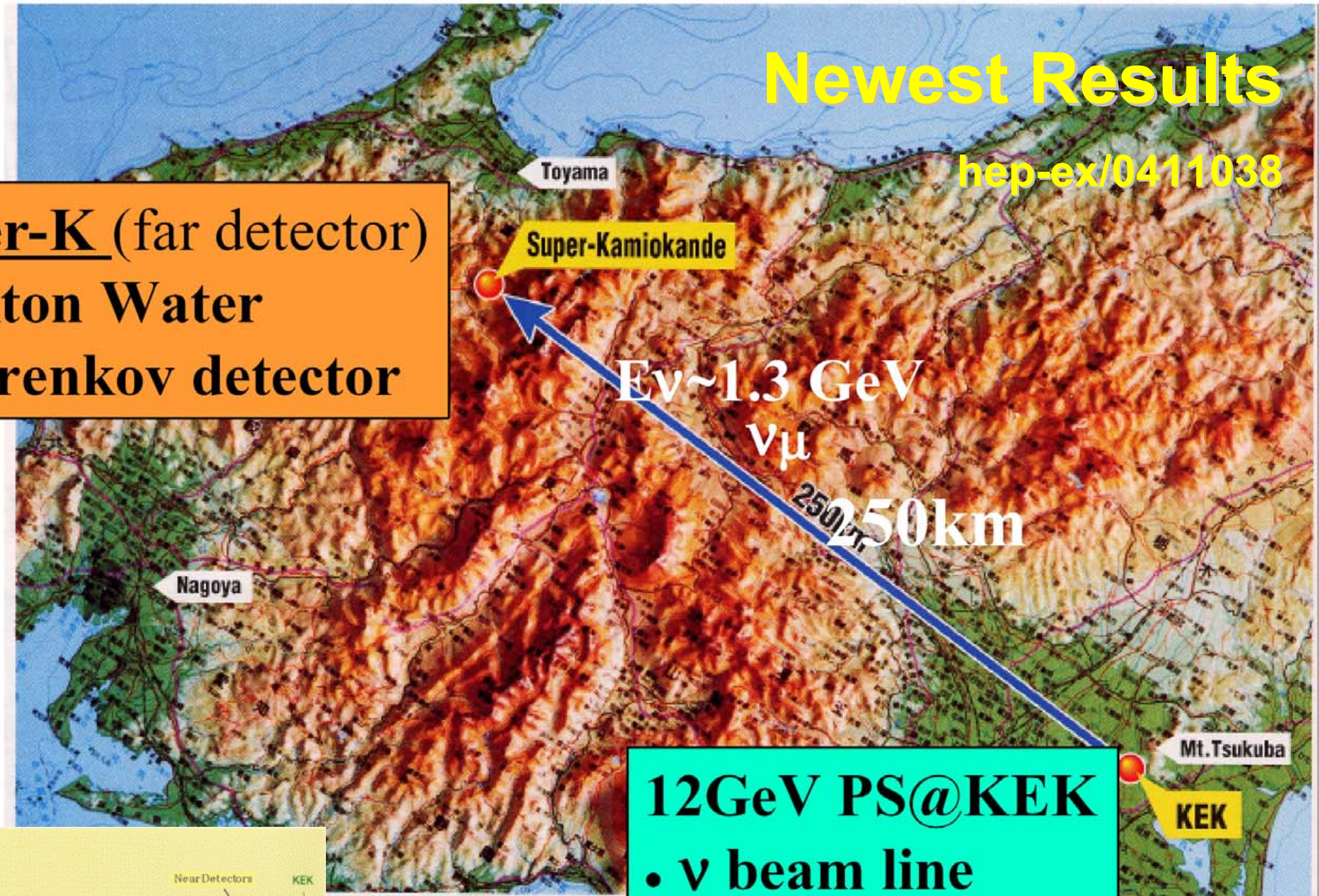
Preliminary!

SK II 311.5days data

- **SK-II data are consistent with SK-I**
- **Clear deficit in upward νμ**

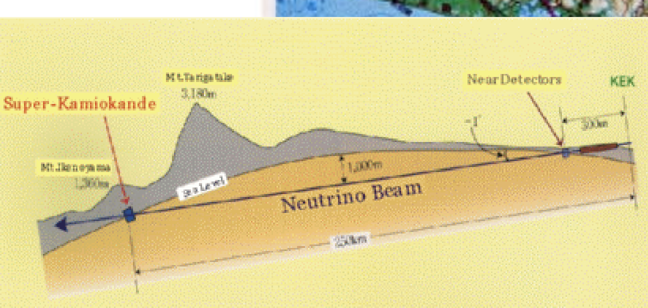
Source: ICHEP 2004

K2K: Neutrinos Produced at Accelerator

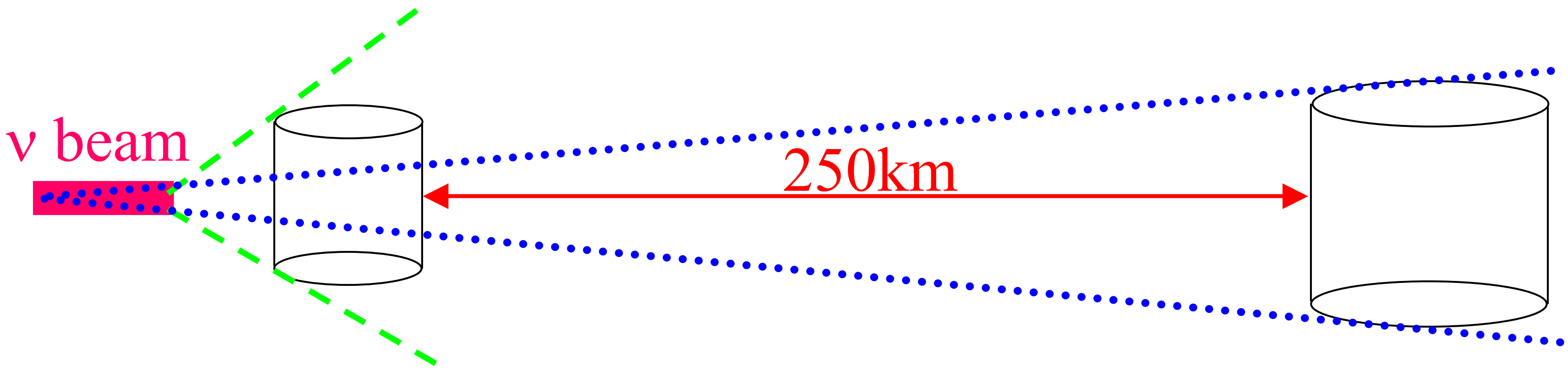


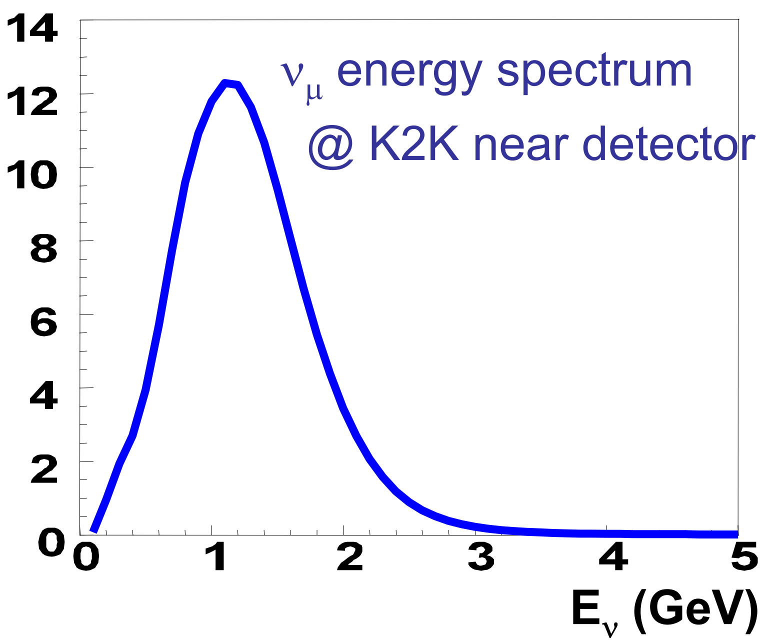
Super-K (far detector)
50 kton Water
Cherenkov detector

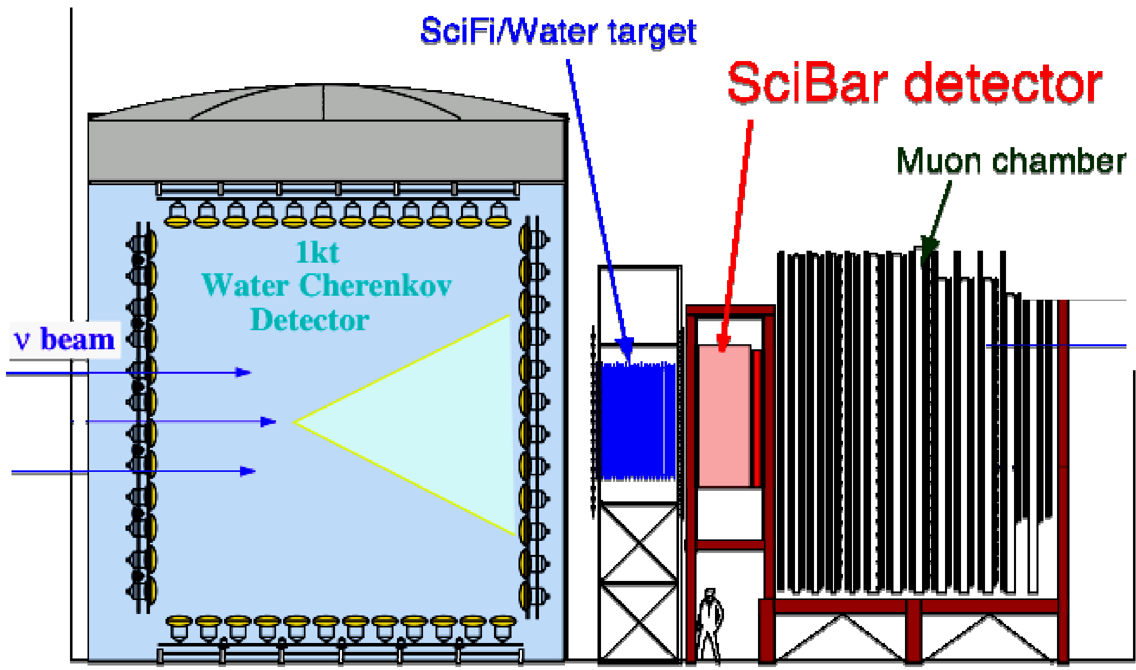
12GeV PS@KEK
- ν beam line
- Beam monitor
- Near detectors



K2K Near Detector







K2K Flux Measurements

- The same detector technology as Super-K.
- Sensitive to low energy neutrinos.

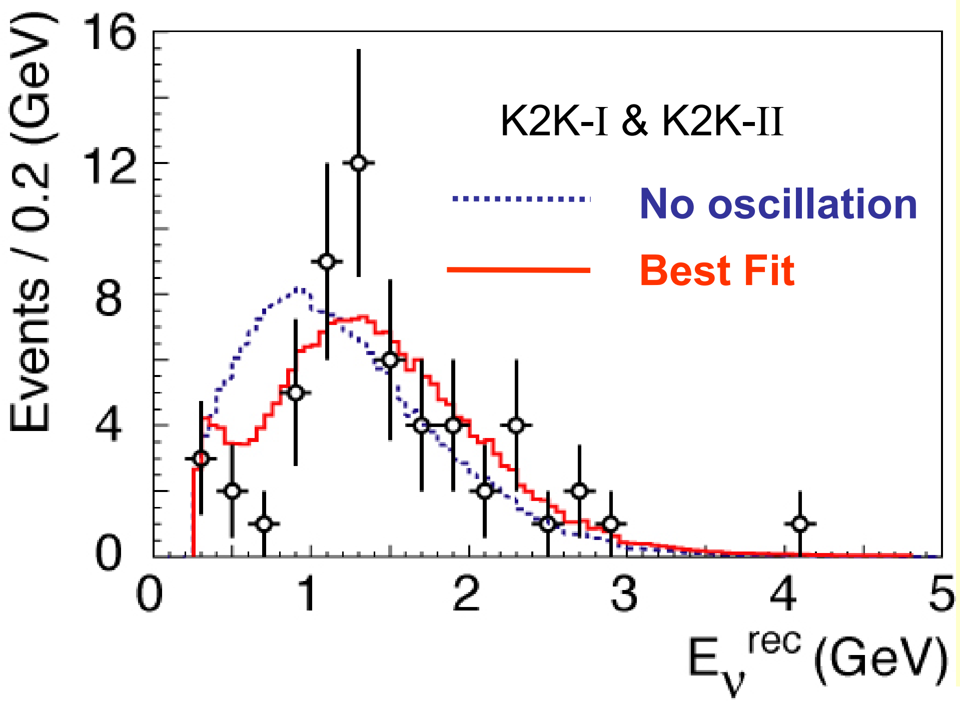
$$N_{SK}^{\exp} = N_{KT}^{obs} \bullet \frac{\int \Phi_{SK}(E_\nu)\sigma(E_\nu)dE_\nu}{\int \Phi_{KT}(E_\nu)\sigma(E_\nu)dE_\nu} \bullet \frac{M_{SK}}{M_{KT}} \bullet \frac{\varepsilon_{SK}}{\varepsilon_{KT}}$$

Far/Near Ratio (by MC)~1×10^{-6}

M: Fiducial mass — M_{SK}=22,500Kton, M_{KT}=25ton

ε: efficiency — $\varepsilon_{SK\text{-}I(II)}$=77.0(78.2)%, ε_{KT}=74.5%

$$N_{SK}^{exp} = 150.9^{+12}_{-10} \quad \longleftrightarrow \text{ no osc. } \quad N_{SK}^{obs} = 107$$



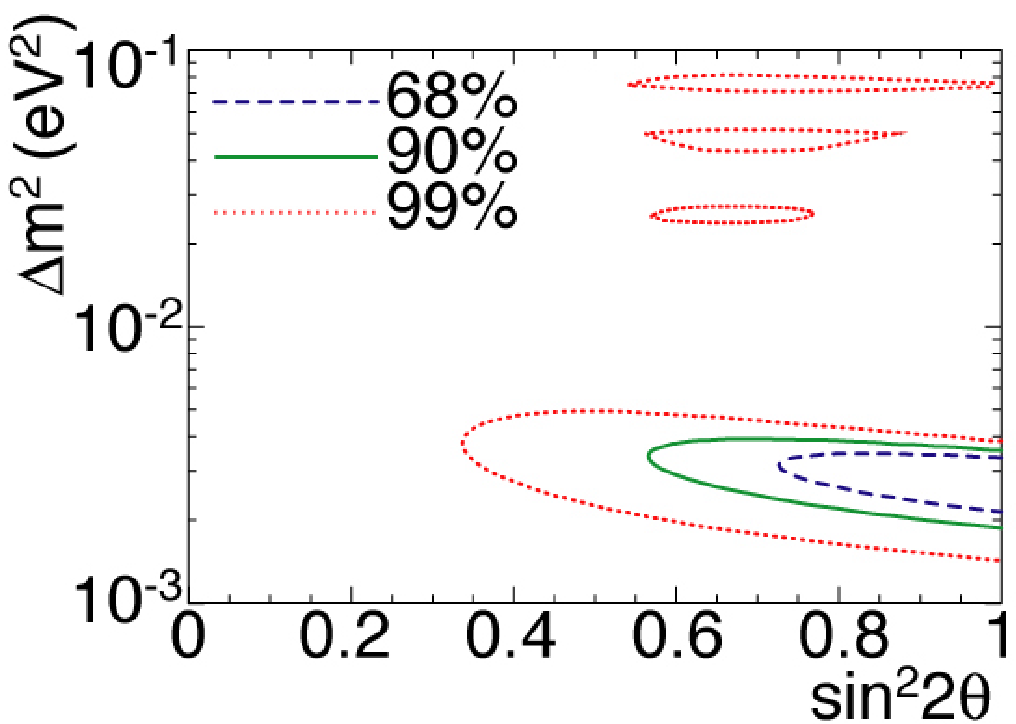
K2K Oscillation $\nu_\mu \leftrightarrow \nu_\tau$ Analysis

Δm^2=2.8x10^{-3},$\sin^2 2\theta$=1.00
from max-likelihood fit

N_{SK}(obs) = 107
N_{SK}(best fit) = 103.8

Distortion of energy spectrum

The probability to see this results if there was no oscillation is 0.005%



Conclusion

- **Neutrino experiments are a very rich probe!**
- **Solar neutrino mixing established by Chlorine, Gallium, SuperK and SNO experiments**
- **Matter effect explains the energy dependence of solar oscillation and SNO solved the solar neutrino <u>problem</u>**
- **Solar solution (LMA) precisely confirmed by KamLAND**
- **SuperK fully solved the atmospheric <u>anomaly</u>**
- **Oscillation parameters from K2K consistent with the atmospheric measurements of SuperK**

"Neutrino oscillation experiments are now part of an industry for precise measurements"