# NEUTRINO OSCILLATIONS

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# BRIEF HISTORICAL BACKGROUND

1955 — pre-quark, pre-parity violation,
pre-Standard Model, pre-etc.

strangeness + associated production of strange particles are established. Among these are the $K^0$ and $\overline{K^0}$ mesons, $J^P = 0^-$.

$$
\begin{array}{lll}
S=+1 & K^0 \rightarrow \pi^+\pi^- & \tau \sim 10^{-10}\,s \\
S=-1 & \overline{K^0} \rightarrow \pi^+\pi^- & m \sim 495\,\text{MeV}
\end{array}
$$

A paper by Gell-Mann + Pais appears

They note $\pi^+\pi^-$ in a state with $CP=+1$ $\left(\begin{array}{c}\text{actually} \\ \text{they used} \\ C\end{array}\right)$

Under the assumption CP is conserved this decay cannot occur since $CP\,K^0 = \overline{K^0}$

But they note the state

$$K_1^0 = \frac{1}{\sqrt{2}}(K^0 + \overline{K^0}) \text{ has } CP=+1$$

$$K_2^0 = \frac{1}{\sqrt{2}}(K^0 - \overline{K^0}) \text{ has } CP=-1$$

Thus $$K^0 = \frac{1}{\sqrt{2}}(K_1^0 + K_2^0)$$

$$\overline{K^0} = \frac{1}{\sqrt{2}}(K_1^0 - K_2^0)$$

What is decaying is

$K_1^0 \to \pi^+\pi$ with CP=+1 $\tau_1 \sim 10^{-10}$ s

They predicted

$K_2^0 \to \pi^+\pi^-\pi^0$ with CP=-1

with $\tau_2 >> \tau_1$

1956 - $K_2^0$ is discovered.

$\tau_2 = .5 \times 10^{-7}$ s

$K^0$ and $\overline{K^0}$ are coherent mixtures of the CP eigenstates $K_1^0$ and $K_2^0$.

Since $K_1^0$ and $K_2^0$ have different lifetimes and different decay modes, they likely have different masses.

In this case you get an oscillatory behavior of the $K_1^0, K_2^0$ content of the $K^0$ with time which depends on $\Delta m = m_{K_2^0} - m_{K_1^0}$ (interference effect)

The measurements show $\Delta m \sim 4 \times 10^{-6}$ eV

$\simeq 4 \times 10^{-12}$ MeV

Compare to $m_K \sim 495$ MeV

# NEUTRINOS

1930 - Pauli hypothesizes the neutrino to explain radioactive $\beta$-decay
neutral, spin $1/2$, very light, interacts weakly

1934 - Fermi makes a theory which evolves into present day weak interaction theory using neutrinos. Basically $n \to p + e^- + \bar{\nu}$
$\nu$ is Dirac or $p \to n + e^+ + \nu$ (in a nucle

1937 - Majorana proposes the possibility
$\nu \equiv \bar{\nu}$ neutrino is its own anti-particle

1956 - Reines + Cowen discover the $\bar{\nu}_e$
by observing $\bar{\nu}_e + p \to e^+ + n$

1957 - Pontecorvo, noting the $K^0$-$\bar{K}^0$ case, looked at other neutral particle-antiparticle systems, in particular $\nu$-$\bar{\nu}$. These would be mixtures of $\nu_1, \nu_2$. If $m_1, m_2$ were small ($m_\nu \neq 0$) but differed you could get oscillations, as in $K^0$-$\bar{K}^0$ system.

1962 - In 1947 $\pi^\pm \to \mu^\pm + \overset{(-)}{\nu}$. Is this $\nu$ different from $\nu_e$.?
Lederman, Schwartz, Steinberger - $\nu$'s from $\pi$ decay
$\nu_\mu + n \to p + \mu^-$ It is different.

Could $\nu_e$ and $\nu_\mu$ be mixtures of states $\nu_1, \nu_2$ of mass $m_1, m_2$.

1975 - The $\tau$ lepton, $\tau^\pm$ is discovered and immediately it is suggested that $\nu_\tau$ exists.

2000 - The $\nu_\tau$ is "discovered" by the DONUT collaboration at FNAL $\quad \nu_\tau + n \to p + \tau^-$

So there are three "flavor" neutrinos, which could be mixtures of three mass eigenstates $\nu_1, \nu_2, \nu_3$ of mass $m_1, m_2, m_3$. Oscillations may occur.

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

## Questions in 1980's

1. Do neutrinos have mass? $m = ?$ Why so light?
2. Are $\nu$'s Dirac ($\nu \not\equiv \bar{\nu}$) or Majorana ($\nu \equiv \bar{\nu}$)?
3. How many $\nu$'s are there?
4. Do $\nu$ flavor oscillations occur?
5. What are $\nu$ magnetic moments?
6. Do neutrinos decay?

1. Yes but $m_\nu$? 2. ?, 3. three active ones, 4. Yes, 5. ?, 6. ?

# OSCILLATIONS

Simplify to the two neutrino case

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

Writing it this way assures unitarity and orthogonal

It follows

$$\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = \begin{pmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Imagine an ideal case. A beam of $\nu_\mu$ of fixed momentum $p$. (e.g. $\xleftarrow{\mu^+} \pi^+ \xrightarrow{\nu_\mu}$)

At $t=0$ $|\nu(0)\rangle = |\nu_\mu\rangle$ pure $\nu_\mu$

For $\nu_1$ and $\nu_2$ : $E_1 = \sqrt{p^2+m_1^2}$ , $E_2 = \sqrt{p^2+m_2^2}$ $(\hbar = c = 1)$

at $t=0$ $|\nu_\mu\rangle = |\nu(0)\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$

at $t$ $|\nu(t)\rangle = -\sin\theta\, e^{-iE_1t}|\nu_1\rangle + \cos\theta\, e^{-iE_2t}|\nu_2\rangle$

substituting $|\nu_1\rangle = \cos\theta|\nu_e\rangle - \sin\theta|\nu_\mu\rangle$ ; $|\nu_2\rangle = \sin\theta|\nu_e\rangle + \cos\theta|\nu_\mu\rangle$

we obtain

$$|\nu(t)\rangle = \sin\theta\cos\theta\left[e^{-iE_2t} - e^{-iE_1t}\right]|\nu_e\rangle + \left[\cos^2\theta\, e^{-iE_2t} + \sin^2\theta\, e^{-iE_1t}\right]|\nu_\mu\rangle$$

$P_{\mu\to e} = \sin^2 2\theta \sin^2\left[\frac{(E_2-E_1)t}{2}\right]$ e appearance

$P_{\mu\to\mu} = 1 - \sin^2 2\theta \sin^2\left[\frac{(E_2-E_1)t}{2}\right]$ $\mu$ disappearance

Now $E = (p^2 + m^2)^{1/2} = p\left(1 + \frac{m^2}{p^2}\right)^{1/2} \approx p\left(1 + \frac{1}{2}\frac{m^2}{p^2}\right)$

$$= p + \frac{m^2}{2p}$$

So
$$E_2 - E_1 = \frac{m_2^2 - m_1^2}{2p} = \frac{\Delta m^2}{2p}$$

In an experiment we measure $L$

$$t = \frac{L}{v} = \frac{L}{p/E} = \frac{LE}{p}$$

$$(E_2 - E_1)t = \frac{\Delta m^2 LE}{2p^2} \approx \frac{\Delta m^2 L}{2E} \quad E \approx p \text{ for } \nu\text{'s}$$

$$P_{\mu\to e} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

This is a maximum for $\frac{\Delta m^2 L}{4E} = \frac{\pi}{2}$

$L = \frac{2\pi E}{\Delta m^2}$ is called the 'oscillation length'

In popular units

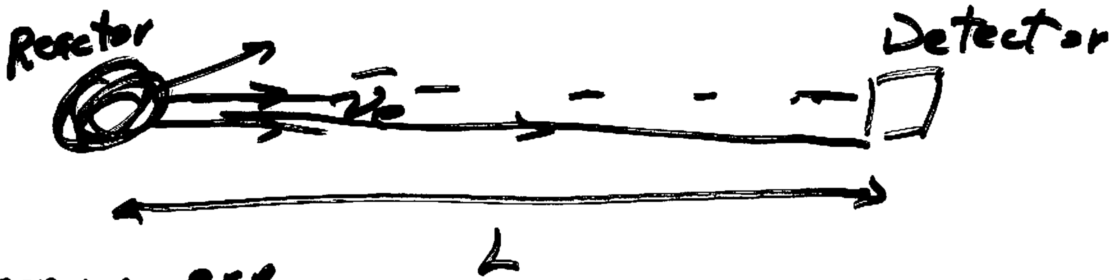
$$P_{\mu\to e} = \sin^2 2\theta \cdot \sin^2\left(1.27 \frac{L}{E} \Delta m^2\right)$$

where $L$ is in meters (kilometers)
$E$ is in MeV (GeV)
$\Delta m^2$ is in eV$^2$

# Early Evidence

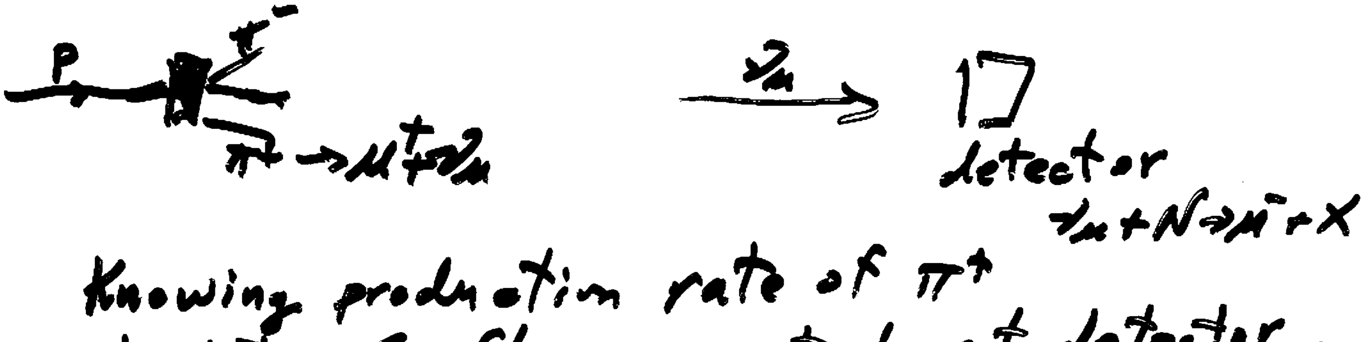
Into the 1980's there had been several experiments at reactors and accelerators looking for $\nu$ oscillations.

Reactors - Huge flux of $\bar{\nu}_e$ coming from
$n \rightarrow p + e^- + \bar{\nu}_e$



Disappearance exp.
Look for deficit of $\bar{\nu}_e$ at the detector

Accelerators - Produce a $\nu_\mu$ beam



Knowing production rate of $\pi^+$ calculate $\nu_\mu$ flux expected at detector.
Look for deficit - Disappearance exp.

Results of all these experiments were
NEGATIVE

Disappearance

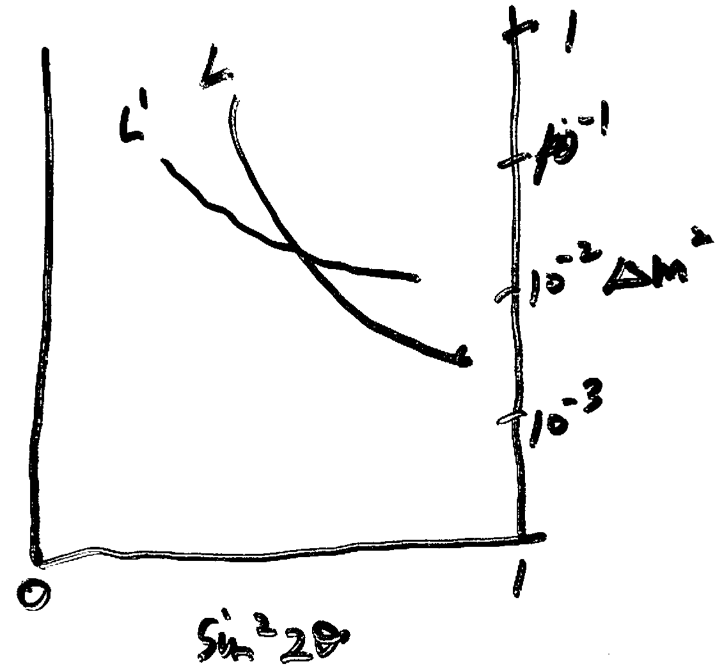
$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{L}{E} \Delta m^2\right)$$

If oscillations exist there are two physical parameters we want to measure

1) $\Delta m^2 = m_2^2 - m_1^2$
2) $\sin^2 2\theta$ - measures the strength of the mixing

If you measure $P_{\mu\mu}$ at a fixed $L$ and $E$ you can't find unique values for $\Delta m^2$ and $\sin^2 2\theta$. You get a contour.

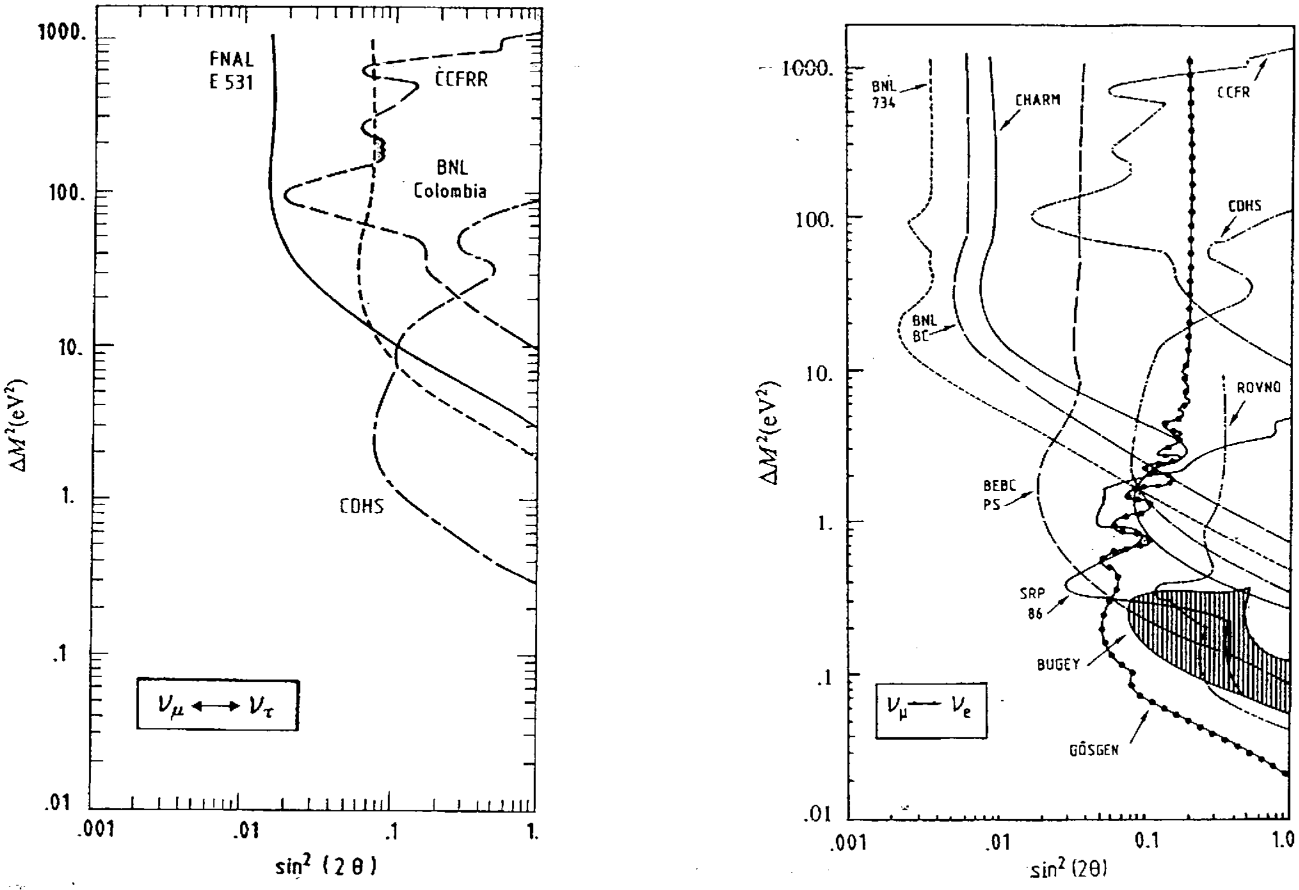
Standard plot



Ideally,
Measure again for a different $L'$ you get another contour. Intersection gives unique point.

Summary of reactor and accelerator experiments up to ~1987. No positive results were seen*, that is $P_{\mu\mu}$ and $P_{ee}$ consistent with $P=1$ ± (these were all disappearance experiments). The contours define exclusion regions - region to the right excluded with 90% confidence.

* The shaded region was claimed to be an allowed region. The experiment claimed $P_{ee} < 1$ as evidence for ν oscillations. By 1988 the claim was withdrawn. A serious error was disovered.



Plots taken from "The Physics of Massive Neutrinos", Boris Kayser 1989

# SOLAR NEUTRINOS

The solar neutrino problem. The Homestake Experiment - tons of cleaning fluid in a tank in the Homestake mine in S. Dakota

$\nu$'s from the Sun

Basic process

$$2e^- + 4p \rightarrow {}^4He^{++} + 2\nu_e + Q$$

with $Q \sim 25$ MeV

Power emitted by sun $P \sim 4 \times 10^{26}$ watts

$P/Q \sim$ # He atoms/sec - for each He there are $2\nu_e$

You can calculate the flux reaching the Earth (approximately)

Homestake reaction

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}\overset{*}{Ar} + e^-$$

Cross section is incredibly small.

~1937 Hans Bethe, creator of the nuclear fusion model of the sun, said: "Can never be observed".

In Homestake about 10 reactions/month are produced in tons of cleaning fluid. Can you find 10 Ar atoms among these tons of Cl-

Finding then won Nobel Prize for Ray Davis. Tons of chlorine are flushed with He gas which carries the argon to another chamber. There the decays of $^{37}Ar^*$ are observed and counted.

Result as of 1980's.

Flux of $\nu_e$'s from sun is $\sim\frac{1}{2}$ of expected!

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Question - What is the explanation?

1) Efficiency of the experiment in detecting argon.
Checked by using an artificial radioactive source emitting $\nu_e$.

2) How good was the theoretical model of the sun? Many concluded this was the problem. Rate of production depends on temperature of core, which is deduced from surface luminosity, other solar features.

SSM

3) Could $\nu_e$'s be oscillating into $\nu_\mu/\nu_\tau$, i.e., disappearing. A mechanism which would enhance this effect as $\nu_e$'s traveled through dense matter from core to surface was proposed. MSW or matter effect.
MSW ≡ Mikheyev, Smirnov, Wolfenstein

# ATMOSPHERIC NEUTRINOS

Cosmic rays, which are 99% protons, impinge on the Earth's atmosphere with a broad energy range. For energies above a few hundred MeV they can produce pions

$$p + \mathcal{N} \rightarrow \pi^+\text{'s} + \pi^-\text{'s} + X$$

Most of these p's interact near the top of the atmosphere $h \sim 20$ km (fortunately for us)

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

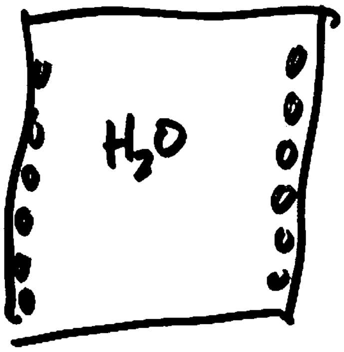
$$\hookrightarrow e^- + \nu_\mu + \bar{\nu}_e$$

We see $\dfrac{\#(\nu_\mu + \bar{\nu}_\mu)}{\#(\nu_e + \bar{\nu}_e)} \approx 2$

In 1980's two large water Čerenkov detectors were in operation, ~ 10 ktons

IMB (ohio)

Kamiokande (Japan)



o photomultiplier tubes PMT's to observe Čerenkov light from charged particle tracks

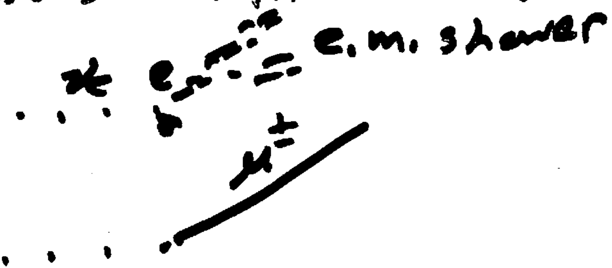
The detectors were designed to search for proton decay, e.g., $p \to \pi^0 e^+$

Background could come from cosmic ray neutrinos, e.g., $\bar{\nu}_e + n \to e^+ + \pi^0 + X$ (not seen).

Therefore they had to understand their BG.

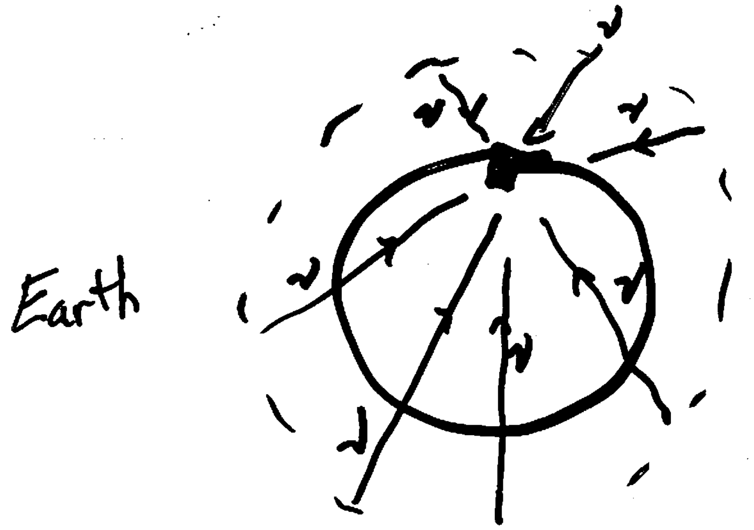
$\overset{(-)}{\nu}_e + n \to e^\pm + X$

$\overset{(-)}{\nu}_\mu + n \to \mu^\pm + X$



They did not find proton decay.

But their BG produced surprising results.



ν's arrive isotropically from all directions.

Define $R = \dfrac{(\nu_\mu/\nu_e)_{data}}{(\nu_\mu/\nu_e)_{expected}}$

Both experiments noted $R < 1$ or $\left(\dfrac{\nu_\mu}{\nu_e}\right)_{data} < \left(\dfrac{\nu_\mu}{\nu_e}\right)_{exp}$

Are there too few $\nu_\mu$ or too many $\nu_e$ ?

In 1988 Kamiokande claimed # $\nu_e$ is as expected, there are too few $\nu_\mu$. $R \sim 0.6-0.7$

They proposed $\nu_\mu \rightarrow \nu_\tau$ oscillations as an explanation! $\Delta m^2 \sim 10^{-2}\,eV^2$
(If it were $\nu_\mu \rightarrow \nu_e$ there would be too few $\nu_\mu$ but too many $\nu_e$)

In 1988 not many people accepted this explanation.

Why ?

1) Statistics were modest and ability to separate $\nu_e$ from $\nu_\mu$ events wasn't yet convincing

2) IMB didn't support it

3) There was a prejudice at the time among some that neutrinos were the best candidate for missing dark matter in the universe.

If so $\sum m_{\nu_i} \approx 10\text{-}30\,\text{eV}$

Most of this could be in $\nu_\tau$

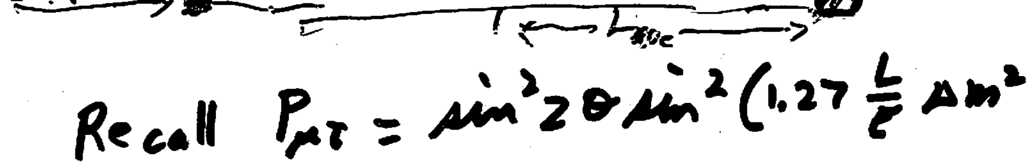
So if $m_{\nu_\tau} \sim 10\text{-}30\,\text{eV}$ and $m_{\nu_e}, m_{\nu_\mu} \simeq 0$

then for $\nu_\mu \to \nu_\tau$ $\Delta m^2 \sim 100\,\text{eV}^2 - 900\,\text{eV}^2$

Ideal experiment for this

Make a $\nu_\mu$ beam at an accelerator, $E \sim 10\,\text{GeV}$

and see $\nu_\tau$ appear via $\nu_\tau + N \to \tau^- + X$



Recall $P_{\mu\tau} = \sin^2 2\theta \sin^2\left(1.27 \frac{L}{E} \Delta m^2\right)$

Ideal L $\quad 1.27 \frac{L}{E} \Delta m^2 = \frac{\pi}{2} \Rightarrow L \sim \frac{\pi}{2.54} \frac{E}{\Delta m^2} \sim 200\,\text{m}$ $\left\{ \begin{array}{l} E \approx 20\,\text{GeV} \\ \Delta m^2 \sim 100\,\text{eV}^2 \end{array} \right.$

Atmospheric $\nu$'s $L = 20 - 13000\,\text{km}$ $\quad E \sim .2 - 10\,\text{GeV}$

## Situation ~ 1990

### Accelerators + Reactors

Null results so far

### Atmospheric Neutrinos

Hint for $\nu_\mu \rightarrow \nu_\tau$ with $\Delta m^2 \sim 10^{-2 \pm 1}\ eV^2$

### Solar Neutrinos

Solar neutrino "deficit" hints at $\nu_e \rightarrow \nu_x$ (Homestake)

*footnote. Supernova 1987A detected in
Kamiokande and IMB via $\nu_e$ interactions
Birth of Neutrino Astronomy

Excitement in the field is running
HIGH

# ~ 1990

# MANY NEW PROPOSALS

**JAPAN** Build SUPERKAMIOKANDE

50 kilotons ~10 X KAMIOKANDE

- Atmospheric $\nu$'s
- Solar $\nu$'s
- Supernovae watch
- proton decay

**U.S.A.** Reactor Palo Verde

Search for $\bar{\nu}_e$ disappearance at longer baseline than earlier experiments

**Accelerators**

- Fermilab NuMI Project (Neutrinos at the Main Injector). Expected to run in 1994 (actual MI 1999 NuMI 2005)

Experiments in NuMI beam

COSMOS - Short baseline 300-400m to search for $\nu_\mu \to \nu_\tau$ in range $\Delta m^2 \sim 10 - 1000$ eV$^2$. cosmological dark matter

MINOS - Long baseline 730km to search $\nu_\mu \to \nu_\tau$ in $\Delta m^2 \sim 10^{-3} - 10^{-1}$ eV$^2$ range - atmospheric effect

- Los Alamos - LSND exp. - Look for $\nu_e$ appearance from $\nu_\mu$

low energy accel. $\pi^+ \to \mu^+ \nu_\mu$

U.S.A **Underground** SOUDAN 2 1 kton iron calorimeter
proton decay, atm. $\nu$'s

## CANADA

SNO (Sudbury Neutrino Observatory)

Solar $\nu$'s in $D_2O$ instead of $H_2O$.
(Used most of Canada's heavy water supply)

## EUROPE

CHORUS
NOMAD

**accelerator** CERN
Short base line experiments to
search for $\nu_\mu \to \nu_\tau$ in $\Delta m^2 \sim 10-1000\, eV^2$ cosmology range

**Reactor** CHOOZ (France) - Search for
$\bar{\nu}_e$ disappearance at longer baselines
$\sim 1$ km

**Solar** Gallium experiments

Italy { GALLEX under Gran Sasso mountain
{ GNO
Russia SAGE in Caucusus

$$\nu_e + Ga \to Ge + e^-$$

**underground** **MACRO** in Italy under Gran Sasso
Monopoles, Astrophysics + Cosmic Ray Observatory
including atm. $\nu$'s

# SOLAR NEUTRINOS

Let's look at the simplest result first.
Number of $\nu_e$'s observed vs. number expected

$$R = \frac{N_e(\text{obs})}{N_e(\text{SSM})}$$

SSM ≡ Standard Solar Model

| Exp. | reaction | R |
|---|---|---|
| Homestake | $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ | $0.34 \pm 0.03$ |
| GALLEX-GNO | $\nu_e + Ga \rightarrow Ge + e^-$ | $0.58 \pm 0.05$ |
| SAGE | " | $0.60 \pm 0.05$ |
| Super K | $\nu_e e^- \rightarrow \nu_e e^-$ | $0.465 \pm 0.018$ |

Consider the disappearance equation for the $2\nu$ case

$$P_{ee} = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{L}{E} \Delta m^2\right)$$

For vacuum oscillations $L \sim 150{,}000{,}000$ km
It's reasonable to expect $L$ represents many, many $\nu$ oscillation lengths. In that case $\overline{\sin^2(\ )} \approx 1/2$

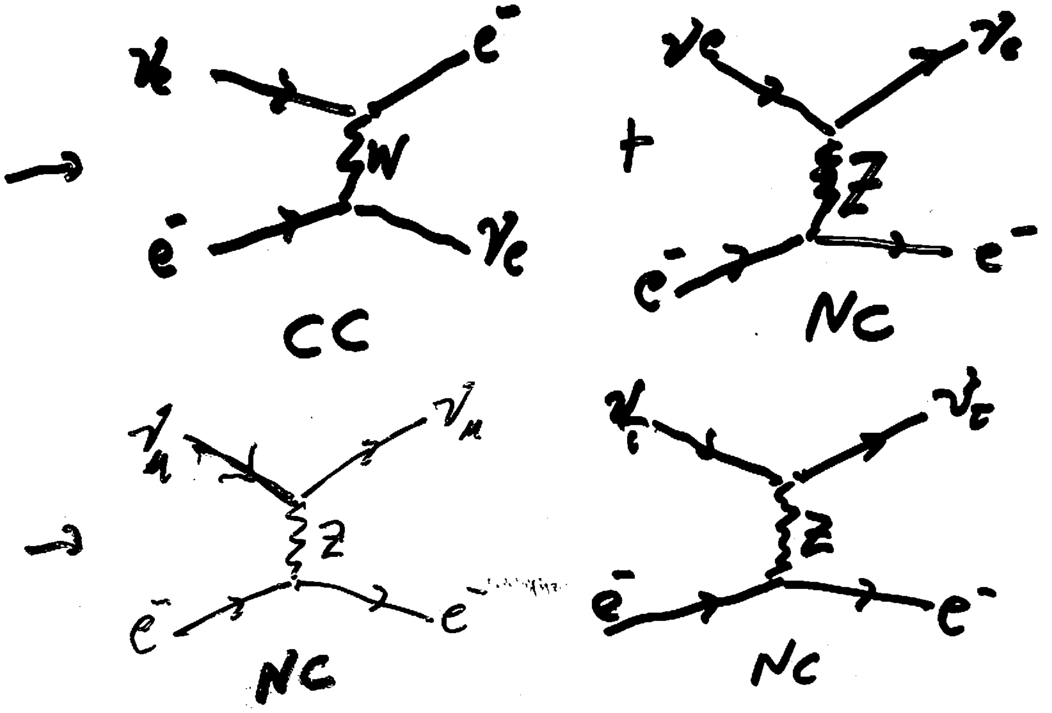
$$P_{ee} \approx 1 - \frac{1}{2} \sin^2 2\theta \gtrsim 0.5 \text{ depending on } \sin^2 2\theta$$

But two results are below 0.5. Suggest vacuum oscillations may not suffice.

# Matter Effects

As ν's travel through matter the weak interaction gives rise to an effective index of refraction (from coherent forward scattering)

But different for $\nu_e$ than for $\nu_{\mu,\tau}$



Pointed out by Wolfenstein in 1978 that this can effect ν oscillations in matter

Mikheyev + Smirnov developed the theory for this in 1984 so its called

MSW effect

They showed that in matter the mixing could be enhanced

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\sqrt{2}\, G_F N_e \frac{2E_\nu}{\Delta m^2} - \cos 2\theta\right)^2}$$

For a given $E_\nu$ and $\Delta m^2$, $N_e$ (the electron density) could take on a value such that

$\sin^2 2\theta_m \approx 1$ even for $\sin^2 2\theta$ small

Solar $\nu$'s are formed in the core of the sun where the density is high. Energies range from 1-10 MeV.

As they pass outward $N_e$ decreases and if they pass through a layer where

$$\sqrt{2}\, G_F N_e = \frac{\Delta m^2}{2E_\nu} \cos 2\theta$$

$\sin^2 2\theta_m \approx 1$ and you get maximal mixing.

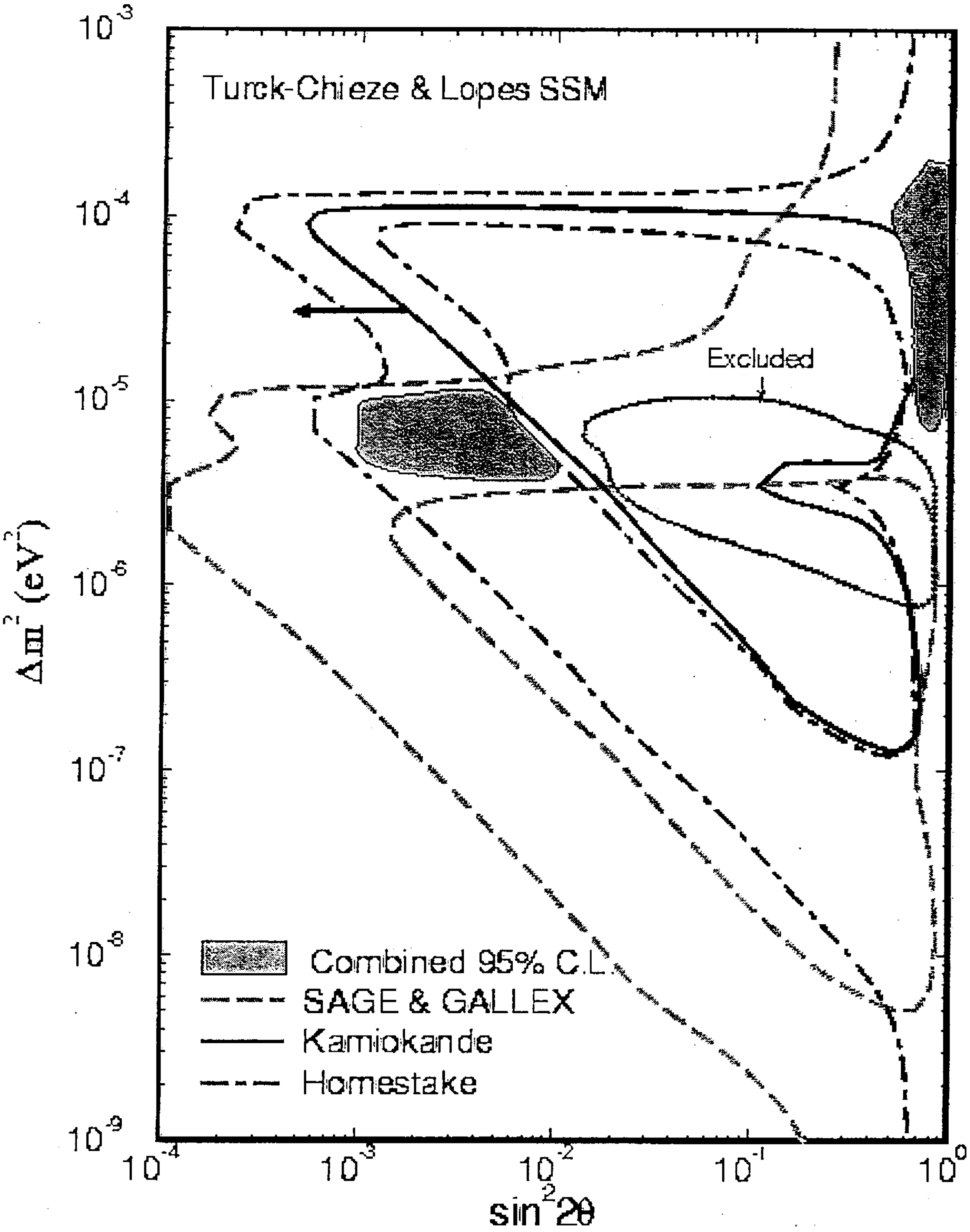


**Figure:** Allowed regions assuming the TCL SSM. From [16,50].

By the years 2000 - 2002 large amounts of data from SuperKamiokande and SNO were arriving

SNO was special

It could look at 3 reactions

1) $\nu_e + d \rightarrow p + p + e^-$ CC

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

3) $\nu_x + e^- \rightarrow \nu_x + e^-$ ES

$x = e, \mu, \tau$

If $\nu_e$ are transforming into $\nu_\mu$ and $\nu_\tau$ 1) and 3) will be reduced from the no oscillation expectation

BUT 2) will remain unchanged since it is produced by $\nu_e + \nu_\mu + \nu_\tau$

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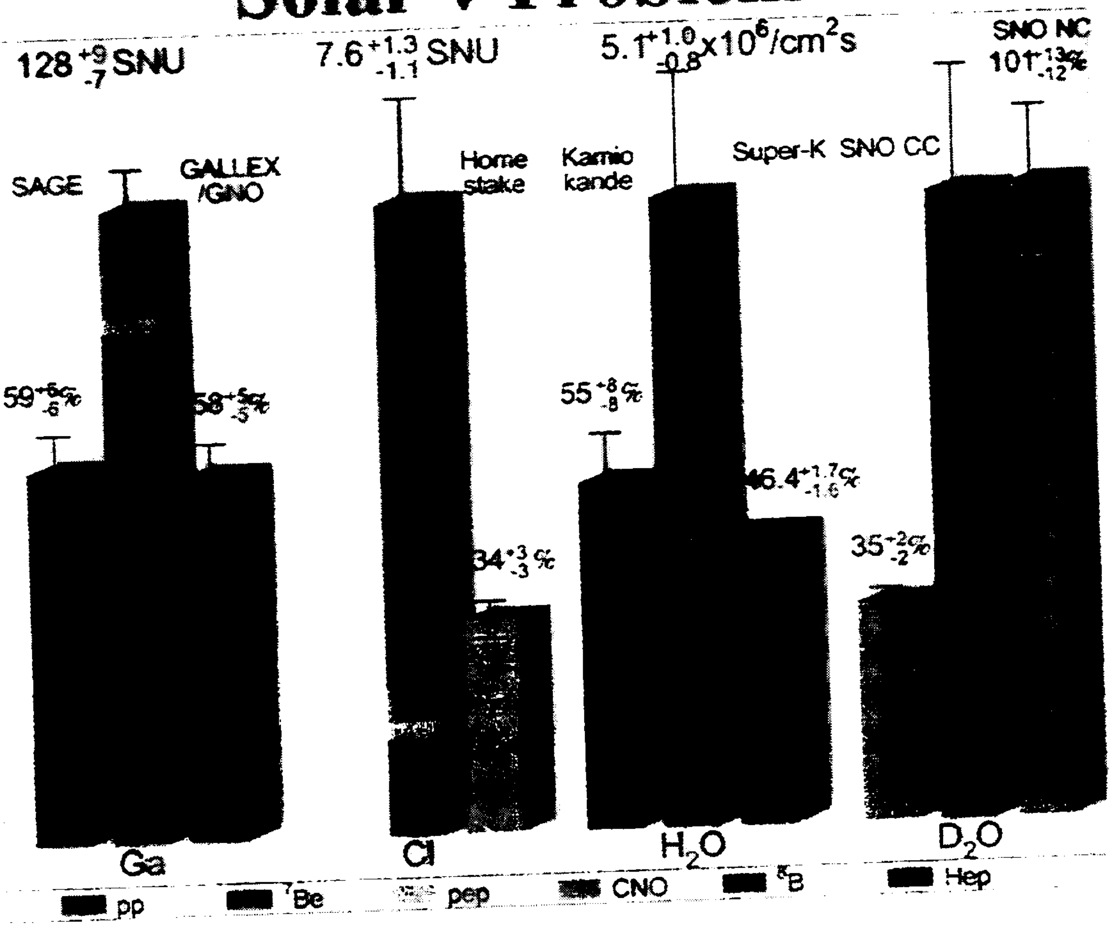
# M. Smy: Super-Kamiokande's Solar Neutrino Results (10/42)

## Solar ν Problem



Michael Smy, UC Irvine

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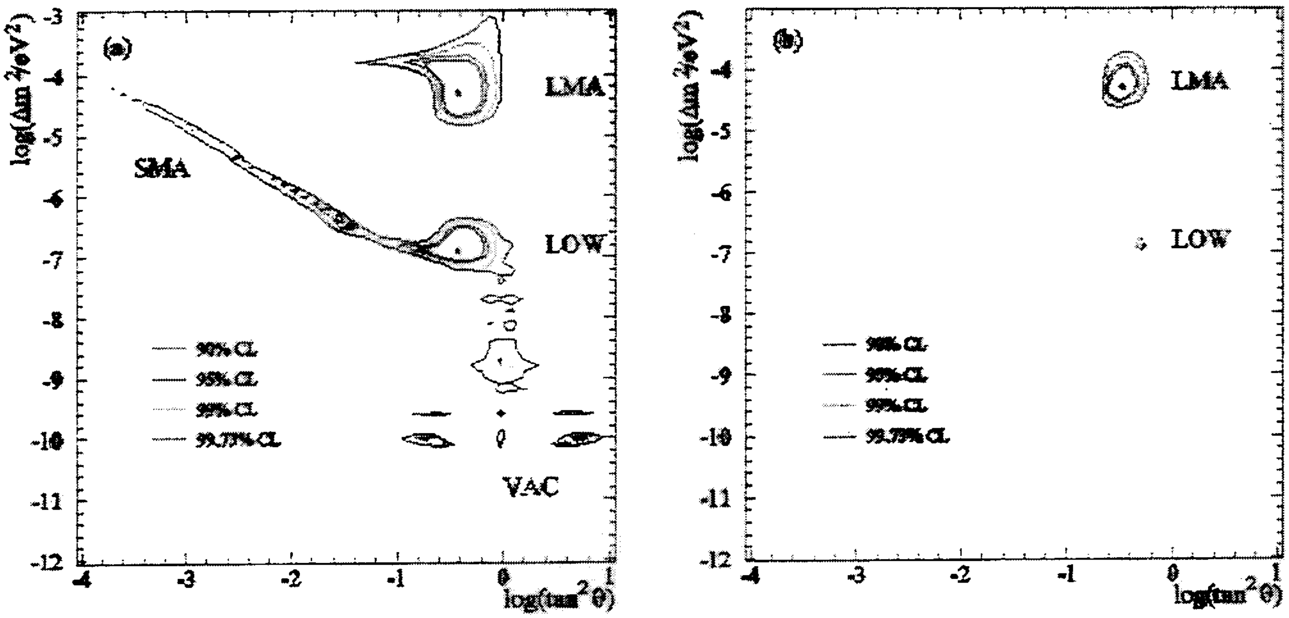
A. Hallin: The Sudbury Neutrino Observatory (27/33)

# Physics Interpretation
# Neutrino Oscillations



**SNO Day and Night Energy Spectra Alone**

**Combining All Experimental and Solar Model information**

# Back to Atmospheric Neutrinos

1995 Super-Kamiokande completed
50 kiloton $H_2O$ Čerenkov

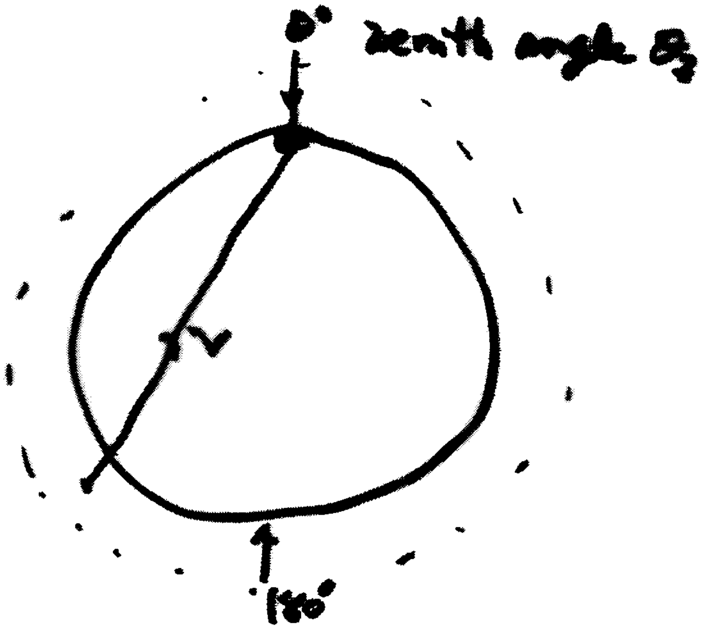
1994 MACRO detector completed
600 tons liquid scintillator + streamer tubes
10,000 $m^2$ acceptance

1993 SOUDAN 2 detector completed

1 kiloton iron calorimeter - fine grained iron and drift tubes

Recall for muon disappearance

$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{L}{E} \Delta m^2\right)$$



For a given neutrino event you can measure

$\theta_z \Rightarrow L$

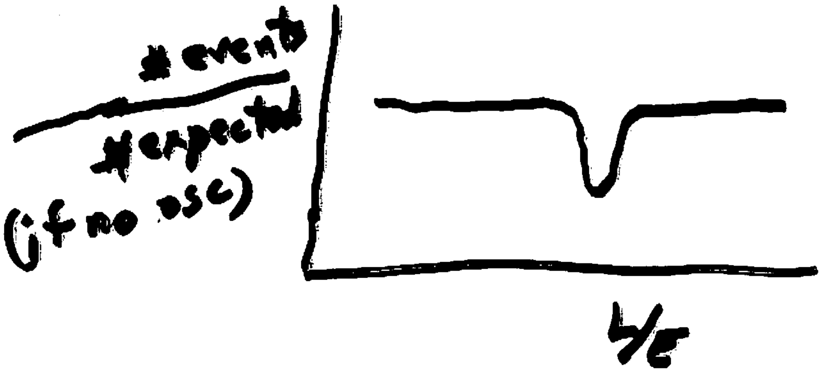
and $E_{vis}$

$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{L}{E_\nu} \Delta m^2\right)$$

Ideally

Measure $L$ and $E_\nu$ for each event.
If oscillations occur you would get a dip in the distribution of $L/E$ compared to no oscillation expectation at

$$\frac{L}{E} = \frac{\pi}{2} \frac{1}{1.27 \Delta m^2}$$



The position of the dip in $\frac{L}{E}$ determines $\Delta m^2$.

The depth of the dip determines $\sin^2 2\theta$.

1) To do this you have to know what is expected.
   a) Start with measured Cosmic Ray fluxes protons hitting the top of the atmosphere
   b) Use measured values, at accelerators of pion production cross sections by protons.
   c) Calculate $\nu_\mu$, $\nu_e$ fluxes from $\pi^\pm \to \mu^\pm + \overset{(-)}{\nu}_\mu$, $\hookrightarrow e^\pm + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu$
   d) measure $\mu^\pm$ fluxes to help

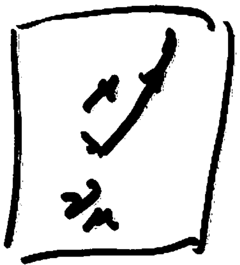
Several groups have worked on this for years, and the calculations are now in good agreement

**Absolute fluxes are good to ± 20%**

**$\nu_\mu/\nu_e$ ratio is good to ± 5%**

Experimentally you measure

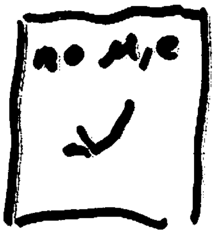
Contained events
ν interacts in detector
SK, Soudan 2



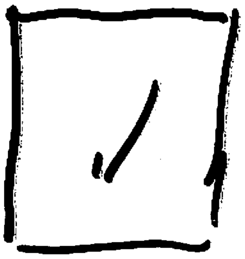
fully contained (FC)

partially contained (PC

FC or PC

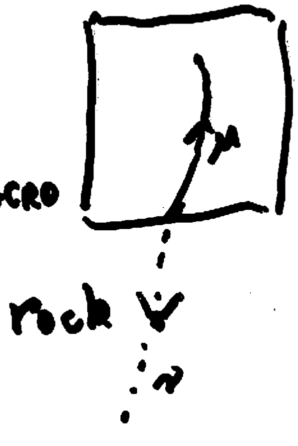


ν neutral current



Background mosty from n

Upward muon events
ν interacts in rock below detector
SK, Soudan2, MACRO



(downward μ's from ν cannot be distinguished from large flux of downward C.R. muons)

Measurements

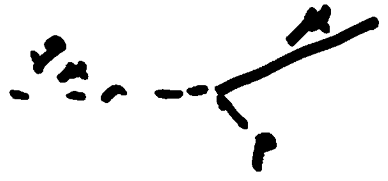
1) Simplest $R = \dfrac{(\nu_\mu/\nu_e)_{data}}{(\nu_\mu/\nu_e)_{exp}}$

integrated over all energies and zenith angles

2) Zenith angle distribution of $\nu_\mu$ and $\nu_e$
integrate over all energies
good when $E$ measurements are not precise

3) $L/E$ distribution. Best but requires
good measurement of $\theta_z$ and $E$

measured
$\theta_z$ is direction of visible momentum in event



e.g. $\nu_\mu + n \to \mu^- + p$

$p$ is often not detectable

the neutron in a nucleus has
Fermi motion

there are measurement errors

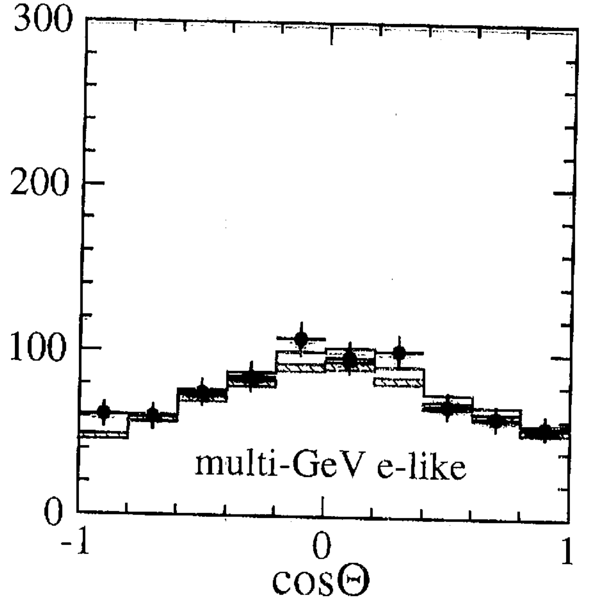
All this leads to smearing which has
to be taken into account

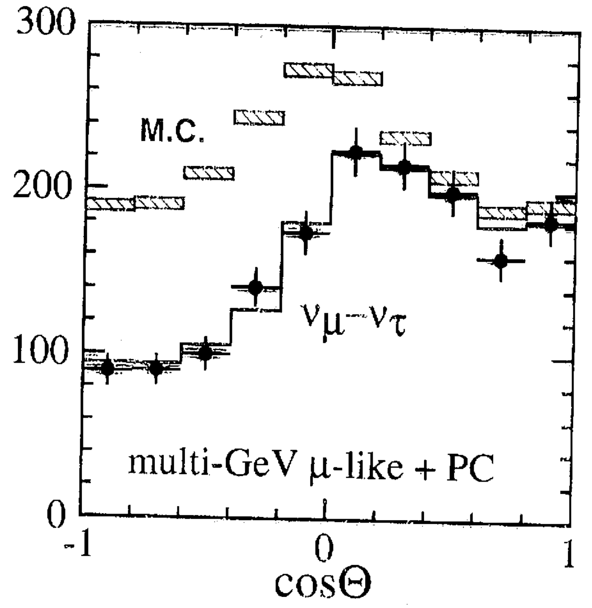
# Super-K Evidence for Neutrino Oscillation

**sub-GeV:** $$\frac{(N_\mu/N_e)_{DATA}}{(N_\mu/N_e)_{M.C.}} = 0.688 \pm 0.016_{\text{stat.}} \pm 0.050_{\text{sys.}}$$

**multi-GeV:** $$\left(\frac{N_{UP} - N_{DOWN}}{N_{UP} + N_{DOWN}}\right)_{\mu\text{-like}} = -0.303 \pm 0.030_{\text{stat.}} \pm 0.004_{\text{sys.}}$$

> 10σ deviation!

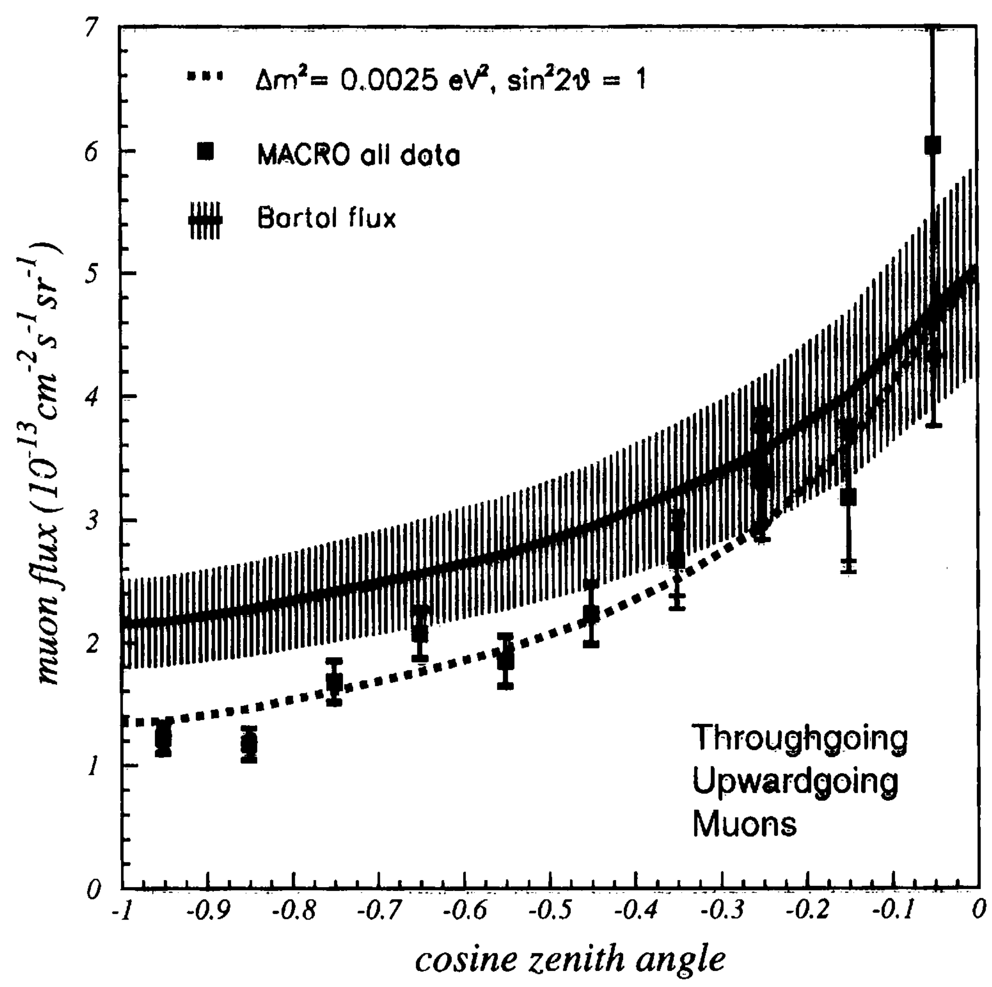




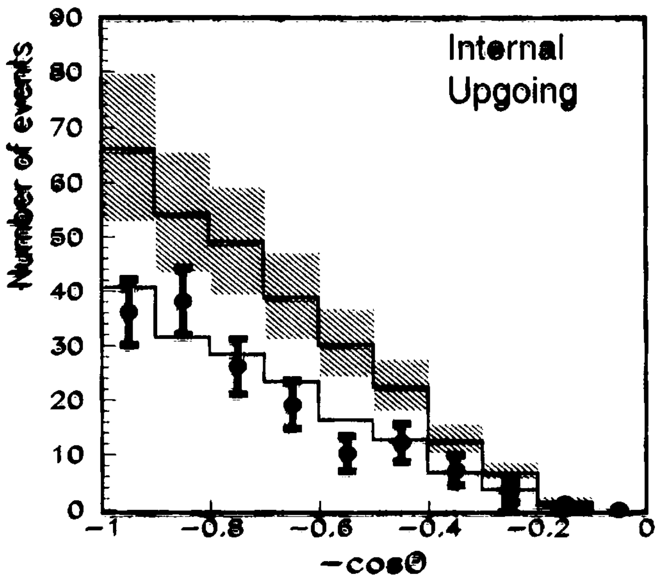
1489 day
Super-K
preliminary

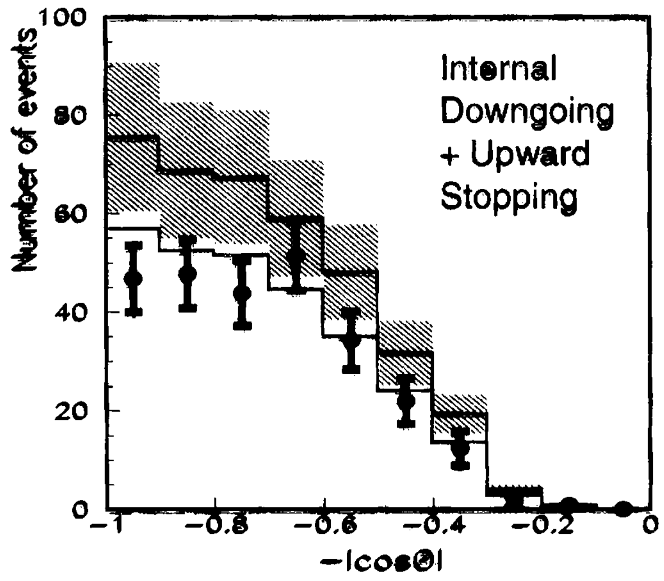
Neutrino travel distance: 12800 6200 700 40 15 km

# MACRO Atmospheric Neutrino Data



See also energy estimate by measuring multiple scattering. Allows for a low resolution plot versus L/E. *See poster by M. Spurio, Nu2002*





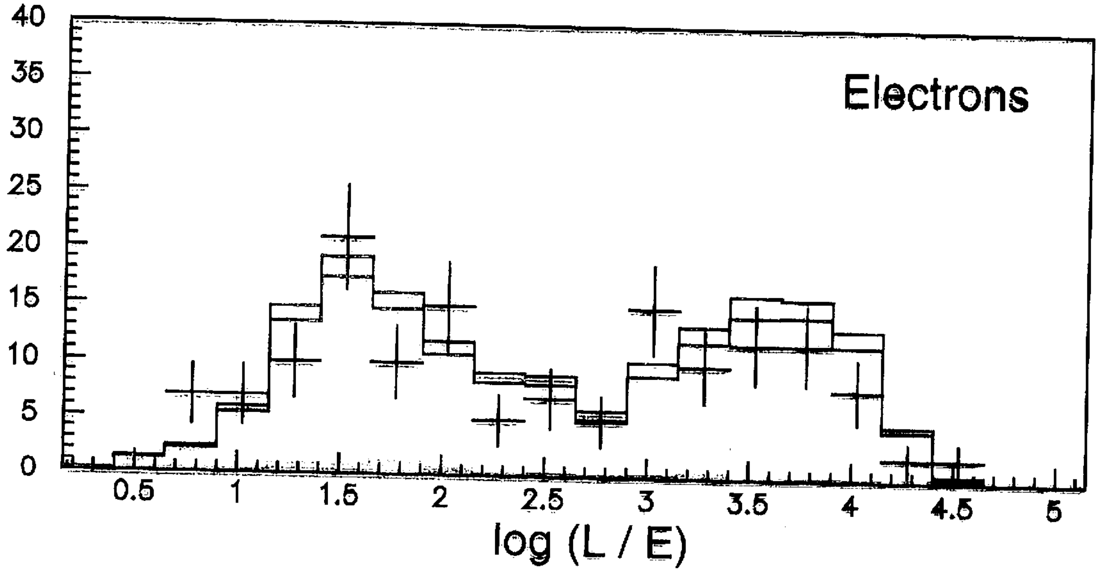
# Soudan 2 High Resolution Sample

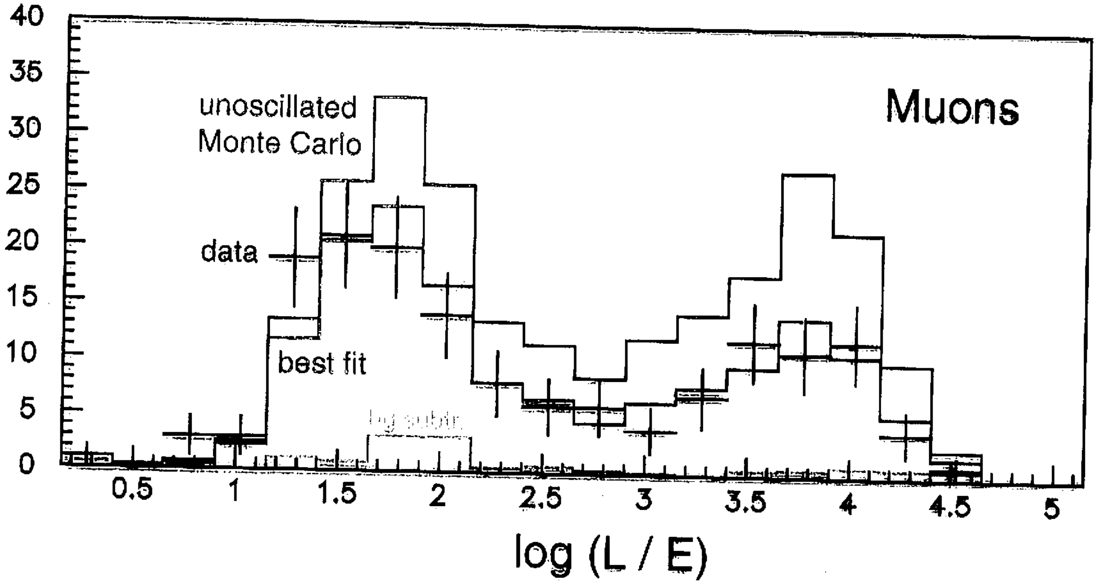
quasi-elastic
- p > 150 MeV/c
  if recoil present
- Evis > 600 MeV
  otherwise

high energy multi-prongs

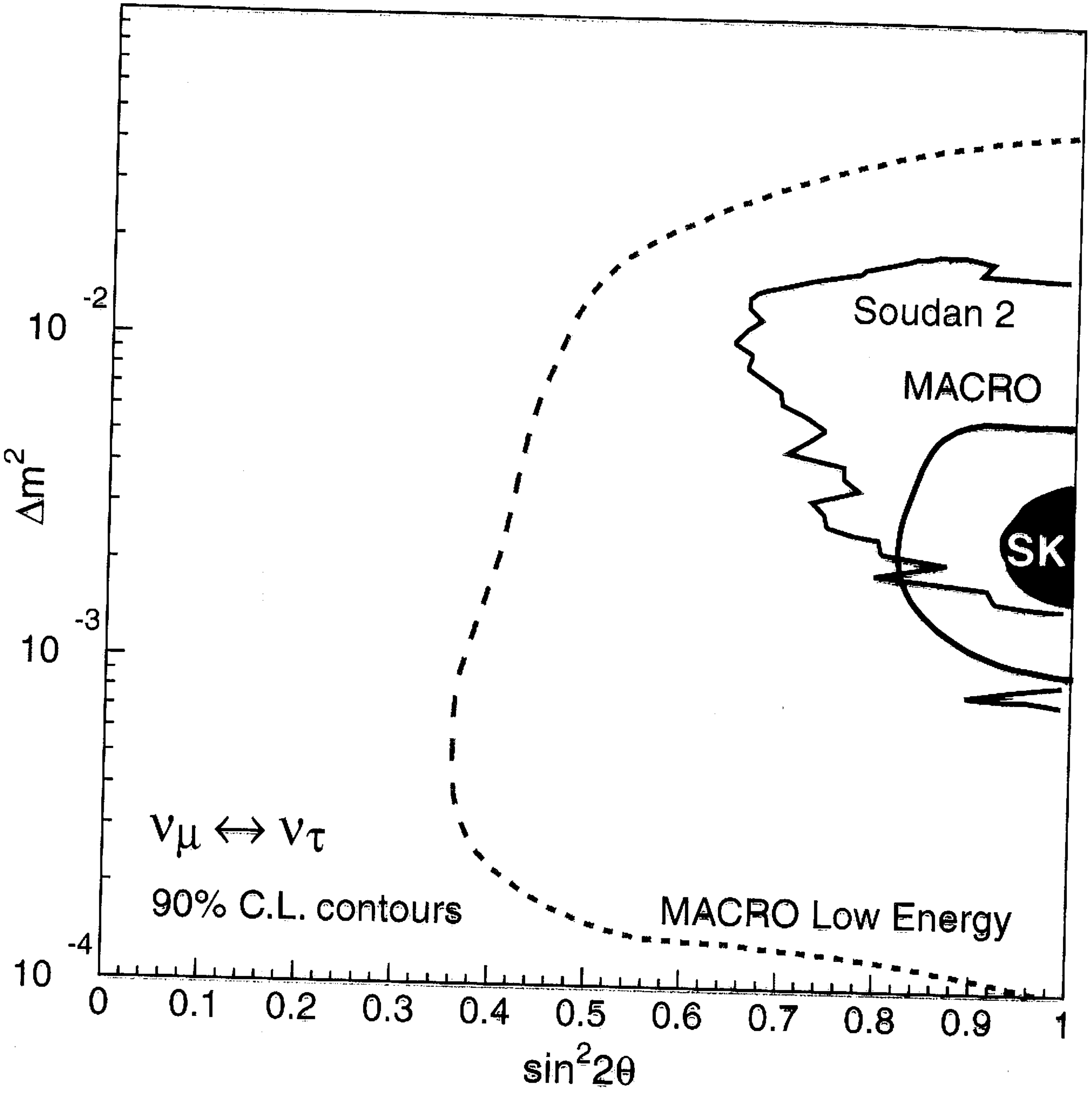
20-30° pointing resolution
log(L/E) resolution ~0.5

data shows suppression
at lower L/E compared
to Super-K:
will allow higher values
of delta $m^2$





# Allowed Regions from Atmospheric Neutrinos



Before considering reactor experiments let's summarize what we know from solar and atmospheric neutrinos.

**Solar** $\nu_e \to \nu_x$ $(\nu_x = \nu_\mu, \nu_\tau)$

described by $\Delta m^2_{12} \sim 7 \times 10^{-5}\, eV^2$

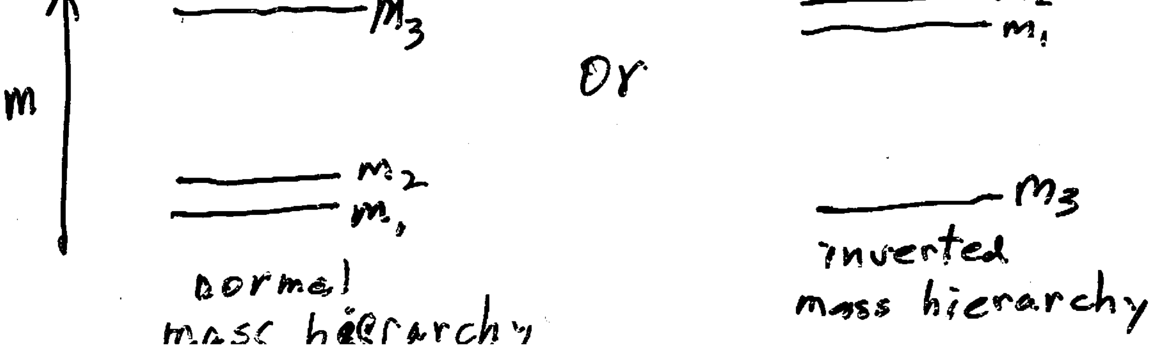
$\tan^2\theta_{12} \sim .4$ $\sin^2 2\theta_{12} \sim 0.8$

**Atmospheric** $\nu_\mu \to \nu_\tau$

described by $\Delta m^2_{23} \sim 2.5 \times 10^{-3}\, eV^2$

$\sin^2 2\theta_{23} \sim 0.9 - 1.0$

These were essentially $2\nu$ analyses. We need to look a little deeper into the $3\nu$ case. They do tell us



Note $\Delta m^2_{13} \approx \Delta m^2_{23}$

# Three ν Formalism

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

or $|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$ and $|\nu_i\rangle = \sum_\alpha U^*_{i\alpha}|\nu_\alpha\rangle$

$$|\nu_\alpha(t)\rangle = \sum_i U_{\alpha i}\, e^{-iE_i t}|\nu_i\rangle$$

$$= \sum_i \sum_\beta U_{\alpha i} U^*_{i\beta}\, e^{-iE_i t}|\nu_\beta\rangle$$

$$P(\nu_\alpha \to \nu_\gamma) = |\langle\nu_\gamma|\nu_\alpha(t)\rangle|^2$$

It was already known from quark mixing (the 3×3 CKM matrix) that such a unitary 3×3 matrix can be described by 4 parameters, usually taken to be 3 angles and 1 complex phase. A standard formulation: (the phase $\delta$ leads to CP violation).

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

where $c_{23} = \cos\theta_{23}$, $s_{23} = \sin\theta_{23}$, etc., but note also $\sin\theta_{13}$

It can be shown that

$$P(\nu_\alpha \to \nu_\gamma) = \left| \delta_{\gamma\alpha} + \sum_{i \geq 2} U_{\gamma i} U^*_{\alpha i} \left( e^{-i \Delta m^2_{i1} \frac{L}{2E}} - 1 \right) \right|^2$$

(see for example hep-ph/0306239, Alberico + Bilenky + references therein)

Consider again the quantity $1.27 \frac{L}{E} \Delta m^2$
for a reactor experiment - $E \sim 3$ MeV.
Suppose $L \sim 10^3$ m $= 1$ km and use $\Delta m_{12}^2 \sim 7 \times 10^{-5}$ eV$^2$

$$1.27 \frac{L}{E} \Delta m_{12}^2 \sim 3 \times 10^{-2} \quad \text{so} \quad \sin^2\left(1.27 \frac{L}{E} \Delta m_{12}^2\right) \sim 10^{-3}$$

Now consider $\Delta m_{13}^2 \approx \Delta m_{23}^2 \approx 2.5 \times 10^{-3}$ eV$^2$

$$1.27 \frac{L}{E} \Delta m_{23}^2 \sim 1 \qquad \sin^2\left(1.22\, L/E\, \Delta m_{23}^2\right) \sim 1$$

Neglecting $\Delta m_{12}^2$ terms it can be shown from above that

$$P(\nu_e \to \nu_e) = P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 4 |U_{e3}|^2 (1 - |U_{e3}|^2) \sin^2\left(1.27 \frac{L}{E} \Delta m_{23}^2\right)$$

These are the parameters of the CHOOZ and PALO ALTO experiments. They find no signal indicating $|U_{e3}|^2 = \sin^2\theta_{13} \lesssim 0.04$ $(\sin^2 2\theta_{13} \lesssim 0.16)$

**How small is $\theta_{13}$? How to measure it?**

Now let us look at the latest reactor experiment **KAMLAND**

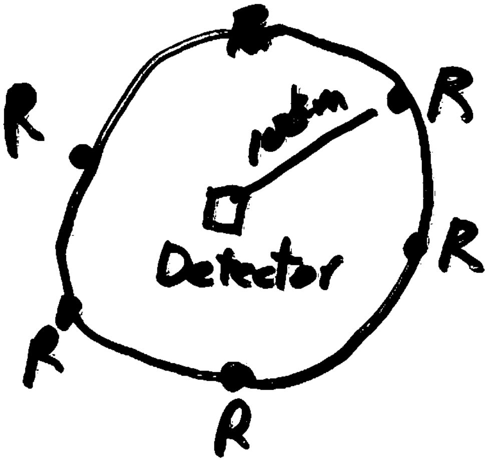
Consider $1.27 \frac{L}{E} \Delta m_{12}^2 = \frac{\pi}{2}$

for maximum effect with $E \sim 5$ MeV for react

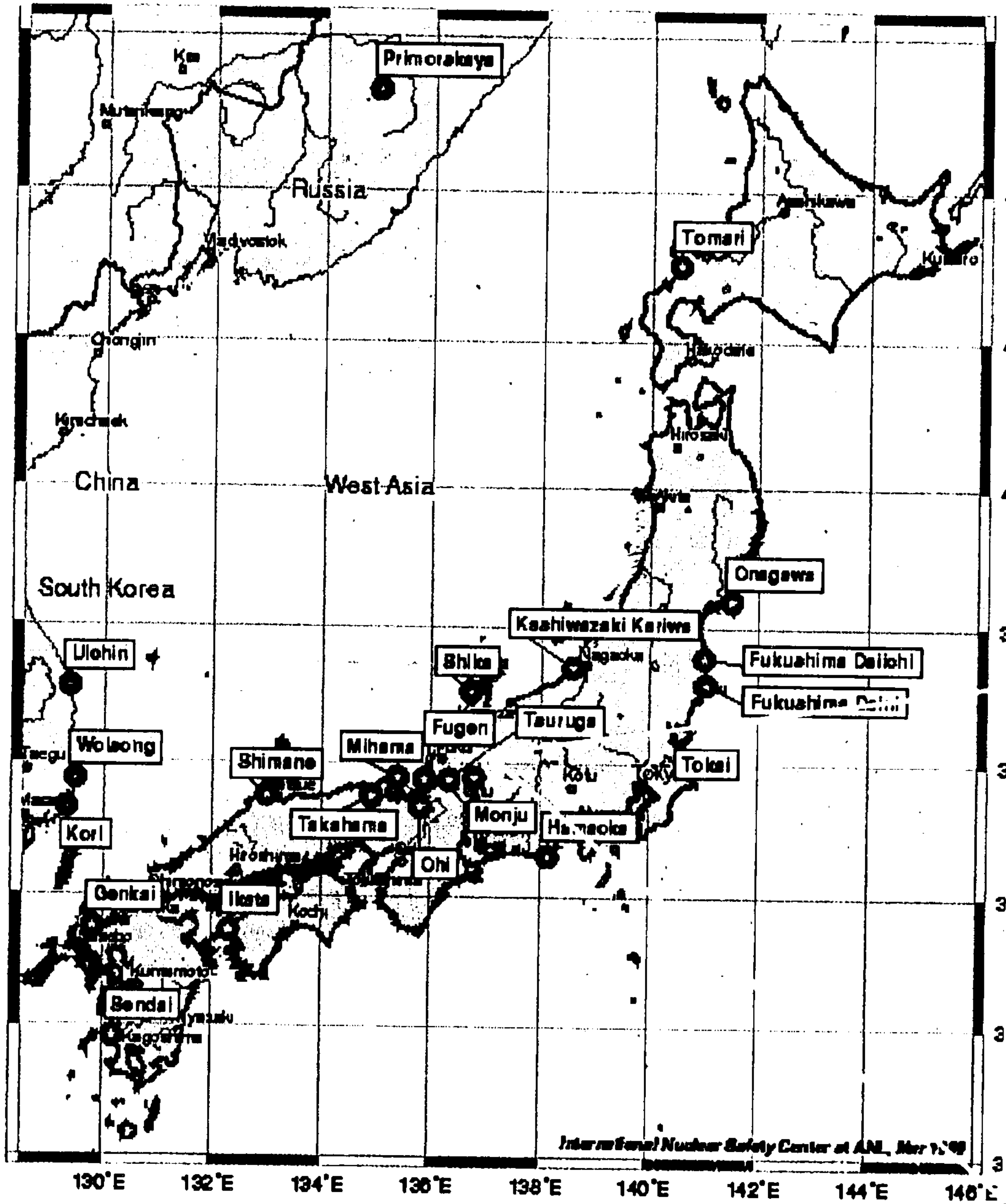
$$L = \frac{\pi}{2.54} \frac{E}{\Delta m_{12}^2} = \frac{\pi}{2.54} \frac{5}{7 \times 10^{-5}} \sim 10^5 m$$

$$= 100 \text{ km.}$$

An ideal experiment would be

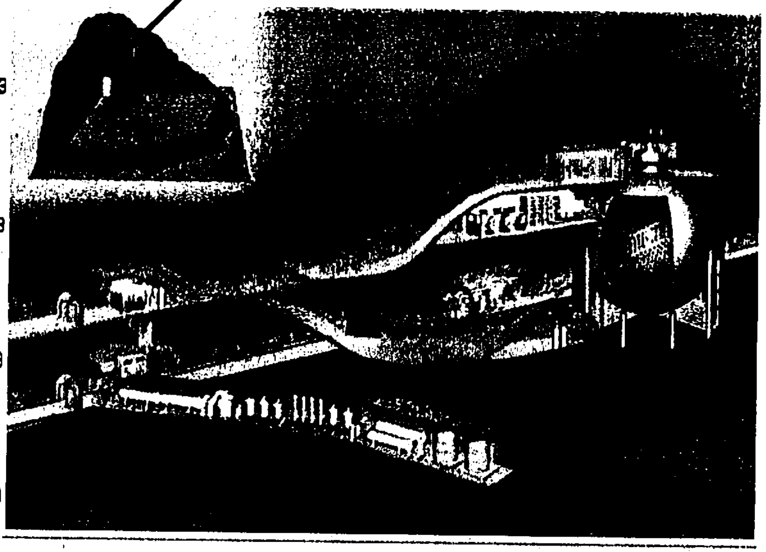


In Japan the Kamioka site approximates this. For the given geometry and reactor powers one can calculate



International Nuclear Safety Center at ANL, Mar 1999

~1 km high
Mt Ikenoyama



$$R = \frac{N_{\bar{\nu}_e}\,(\text{data})}{N_{\bar{\nu}_e}\,(\text{expected, no oscill.})}$$

At various times some of the reactors are off for maintenance work. This results in a different value of R.

From all the data up to now the most recent KAMLAND result is

$$\Delta m^2_{12} = 8.3 \times 10^{-5}\ \text{eV}^2$$

$$\sin^2 2\theta_{12} = 0.83$$

in excellent agreement with the results of the solar neutrino analysis. For the first time the solar $\nu$ oscillation effect is measured in a terrestrial exp.

Can the atmospheric neutrino oscillations be seen in an accelerator experiment?

$$\Delta m_{23}^2 \simeq 2.5 \times 10^{-3}\, eV^2$$

$$\sin^2 2\theta_{23} \approx 1$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2 1.27 \frac{L}{E} \Delta m^2$$

1990 - Proposal to send a $\nu$ beam from Fermilab to the Soudan mine in Minnesota $L = 730$ km using new Main Injector

Approved in 1995 - the MINOS experiment Will run in early 2005.

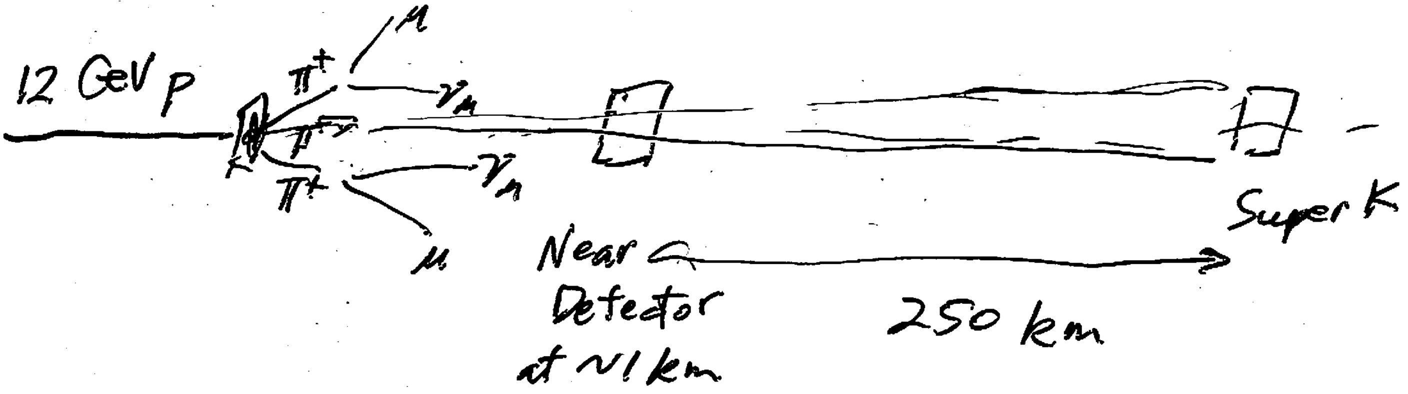
1995 - Japanese - U.S. groups proposed sending a beam from KEK accelerator to Super-Kamiokande. $L = 250$ km. Began running in 1999. Now finished.

We want $1.27 \frac{L}{E} \Delta m^2 \sim \pi/2$

$L = 730$ km $\quad E \approx \frac{2.54 L \Delta m^2}{\pi} \simeq 1.5$ GeV

$L = 250$ km $\quad E \approx 0.5$ GeV

## Neutrino beam at KEK



The neutrino beam has a broad energy spectrum. At KEK 0.3 - 3 GeV. Compare data at far detector from what is expected, based on near detector measurements.

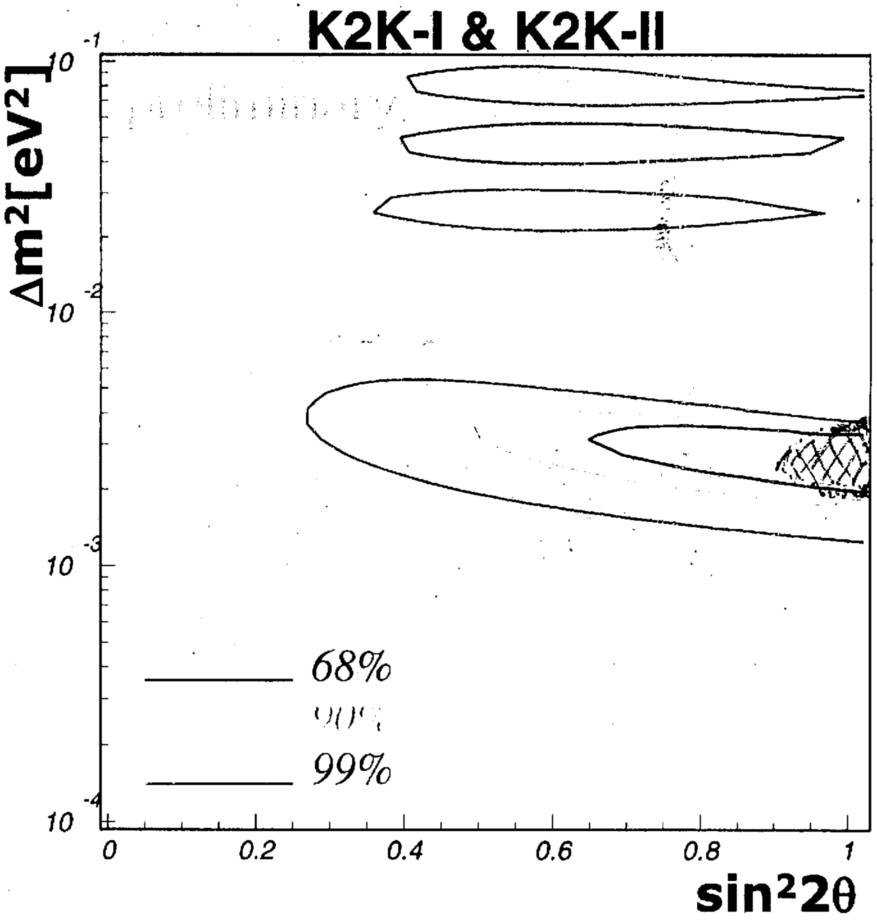
$$P_{\mu\to\mu} = 1 - \sin^2 2\theta_{23} \sin^2\left(1.27 \frac{L}{E} \Delta m_{23}^2\right) \text{ (average over } E \text{ spectrum)}$$

Measure $P_{\mu\mu} = \frac{N(\text{observed})}{N(\text{expected})}$

See a dip in the energy spectrum at $E \sim 0.5$ GeV

For no oscillations
N(expected) = 159 events

# Data are consistent with the oscillation.

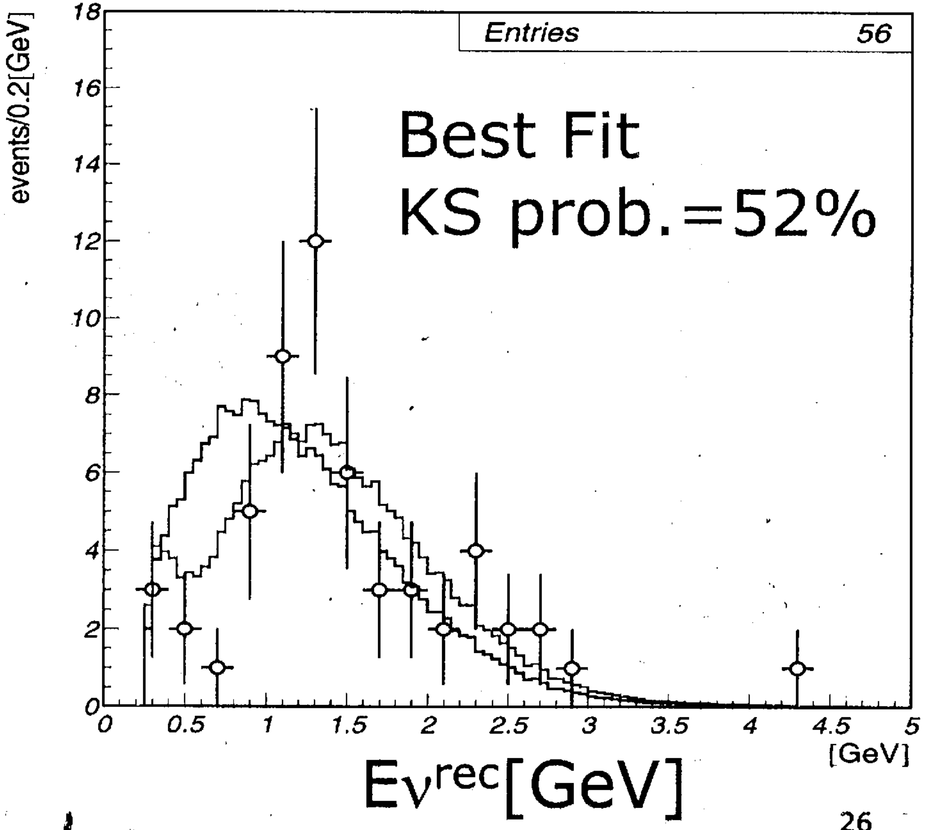


**Based on $\Delta \ln L$**

Best fit $\Delta m^2 = 2.73$ eV$^2$
$\sin^2 2\theta_{23} = 1$

☆ atmospheric
[illegible]

- $N_{SK}^{obs}=108$
- $N_{SK}^{exp}$ (best fit)$=104.8$



# WHAT DO WE KNOW NOW?

$$\left.\begin{array}{l}\sin^2 2\theta_{12} \sim 0.8-1.0 \\ \Delta m_{12}^2 \sim (0.7-0.9)\times 10^{-5}\,\mathrm{eV}^2\end{array}\right\}\text{Solar + KAMLAND}$$

$$\left.\begin{array}{l}\sin^2 2\theta_{23} \sim 0.9-1.0 \\ \Delta m_{23}^2 \sim (2-4)\times 10^{-3}\,\mathrm{eV}^2\end{array}\right\}\text{Atmospheric + K2K}$$

$$\sin^2 \theta_{13} \lesssim 0.04$$

# WHAT WE DON'T KNOW (YET)

Mass hierarchy - normal ($m_1 < m_2 < m_3$) or
inverted ($m_3 < m_2 < m_1$)

Majorana ($\nu \equiv \bar{\nu}$) or Dirac ($\nu \neq \bar{\nu}$)

Absolute mass values $m_1, m_2, m_3$

mixing angle $\theta_{13}$ - how small is it

$\delta$ the CP violating phase factor

IT LOOKS LIKE THINGS ARE COMING ALONG AND NEW EXPERIMENTS ARE GETTING READY

BUT THERE IS A FLY IN THE OINTMENT

IT IS CALLED

LSND (at Los Alamos, 1990's)

(Liquid Scintillator Neutrino Detector)

Consider $\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\qquad\qquad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

Expected neutrino reactions

$\nu_\mu + N \rightarrow \mu^- + X$

$\bar{\nu}_\mu + N \rightarrow \mu^+ + X$

$\nu_e + N \rightarrow e^- + X$

But No $\bar{\nu}_e + N \rightarrow e^+ + X$

LSND Claims observation of $\bar{\nu}_e + N \rightarrow e^+$

The only explanation seems to be an oscillation $\bar{\nu}_\mu \to \bar{\nu}_e$. Analysis gives $\Delta m^2 \sim 1\ \text{eV}^2$

But three different $\Delta m^2$ values would require 4 neutrinos.

The famous LEP and SLAC results from $Z^0 \to \nu\bar{\nu}$ tell us there are just 3 active neutrinos

↓ have weak interaction

Two possible explanations

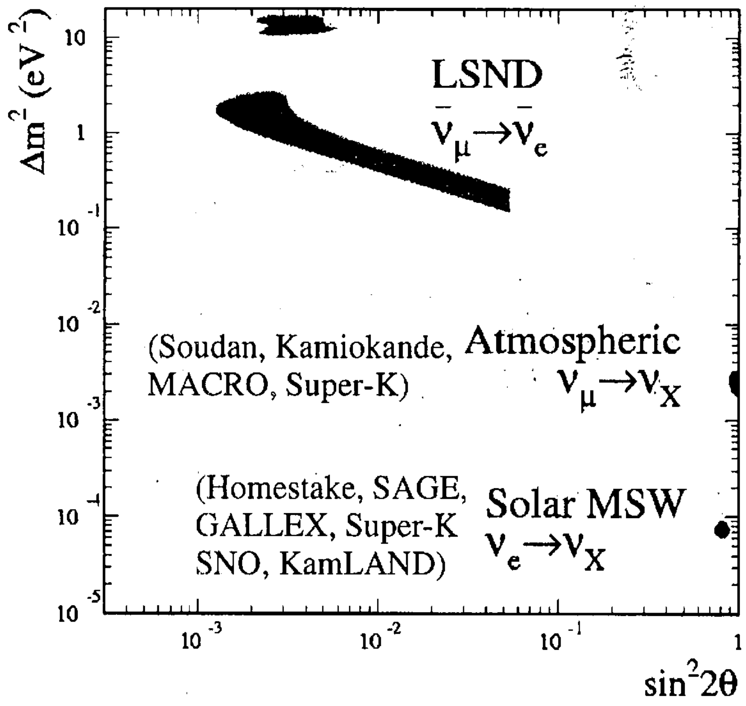
1. The experiment is somehow wrong
2. There is a fourth neutrino, but sterile, does not partake in the weak interaction, $\nu_s$.

An experiment at Rutherford Laboratory

KARMEN

does not support LSND, but is not sensitive enough to rule it out.

# Current Oscillation Signals



- Unconfirmed
  - $\Delta m^2_{LSND} \sim$ 0.1-10 eV$^2$
- Well established measurements
  - $\Delta m^2_{atm} \sim 2 - 3 \times 10^{-3}$ eV$^2$
  - $\Delta m^2_{solar} \sim 7 \times 10^{-5}$ eV$^2$

# OUTLOOK

13 Questions posed by B. Kayser at NU2002

- Do neutrinos truly oscillate in flavor ?
- How many $\nu$'s are there? Sterile $\nu$'s ?
- What are the masses of the mass eigenstates $\nu_i$ ? why so light ?
- Are the mass eigenstates Majorana or Dirac ?
- What are the elements of $U$ (mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$)?
- Does $U$ contain CP violating phases, $\delta$ ? Observable ?
- Was baryogenesis in early universe due to leptonic CP violation?
- Do the properties of $\nu$'s and $\bar{\nu}$'s violate CTP invariance?
- What can neutrinos tell us about astrophysics and cosmology ?
- Can $\nu$'s probe extra spatial dimensions ?
- What are the em properties of $\nu$'s. Magnetic + electric dipole moments ?
- Do neutrinos decay ? If so how fast, into what ?
- What is the origin of $\nu$ flavor physics ? Is it new physics at a high mass scale ? What is the new physics and the mass scale ? What is the connection between neutrino flavor physics and quark flavor physics ?

These 13 Questions tell you why we are devoting so much effort to neutrino physics.

We've had glimpses of a program that's come a long way, but has a long way to go. We've indicated proposals stretching out some 20-30 years in the future.

The next important result will be summer 2005. Will MiniBooNE confirm LSND, or not. If yes, things get more complex.

Perhaps by the year 2030 we will have all the answers. That would be the appropriate way to celebrate the 100th anniversary of Pauli's neutrino hypothesis!

# Some References

1. The web sites of all the experiments - past, present and proposed future - discussed in this lecture.

2. For a recent overview the paper by Boris Kayser
   Proceedings of NEUTRINO 2002 conf.
   also hep-ph/0306072

3. For phenomenology of oscillations
   Phenomenology of Neutrino Oscillations
   S.M. Bilenky, C. Giunti, W. Grimus
   Progress in Particle + Nuclear Physics 43 (199
   1-86

4. Web sites of conferences
   NEUTRINO 2004 + Proceedings
   NUFACT 2004
   NEUTRINO 2002 etc.

All of the above contain dozens of additional references