Super-Kamiokande: The Road to Neutrino Oscillations

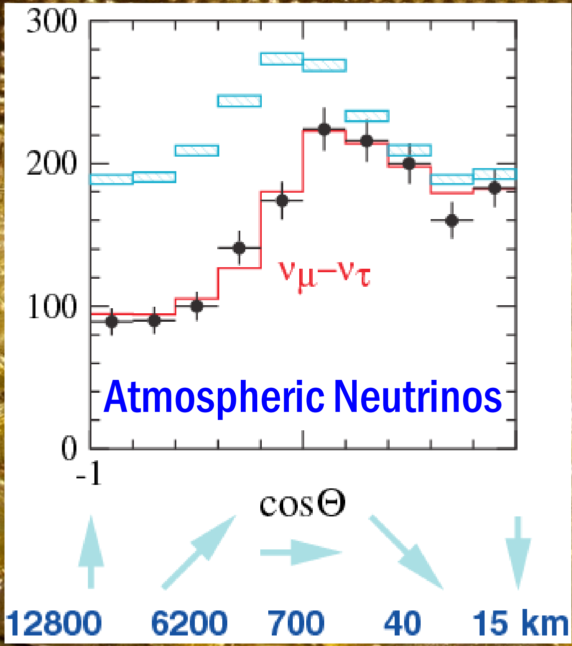
James Stone

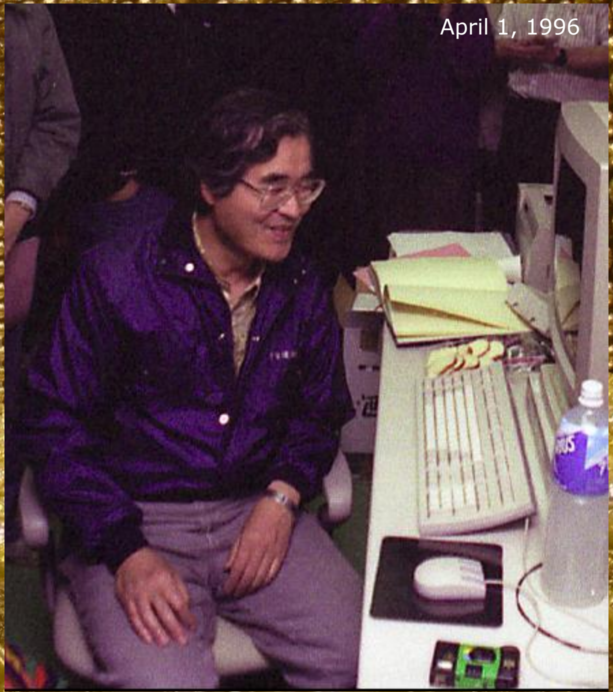
Boston University

A Symposium on the Occasion of the **Benjamin Franklin Medal** for the Experimental Discovery of Neutrino Oscillations

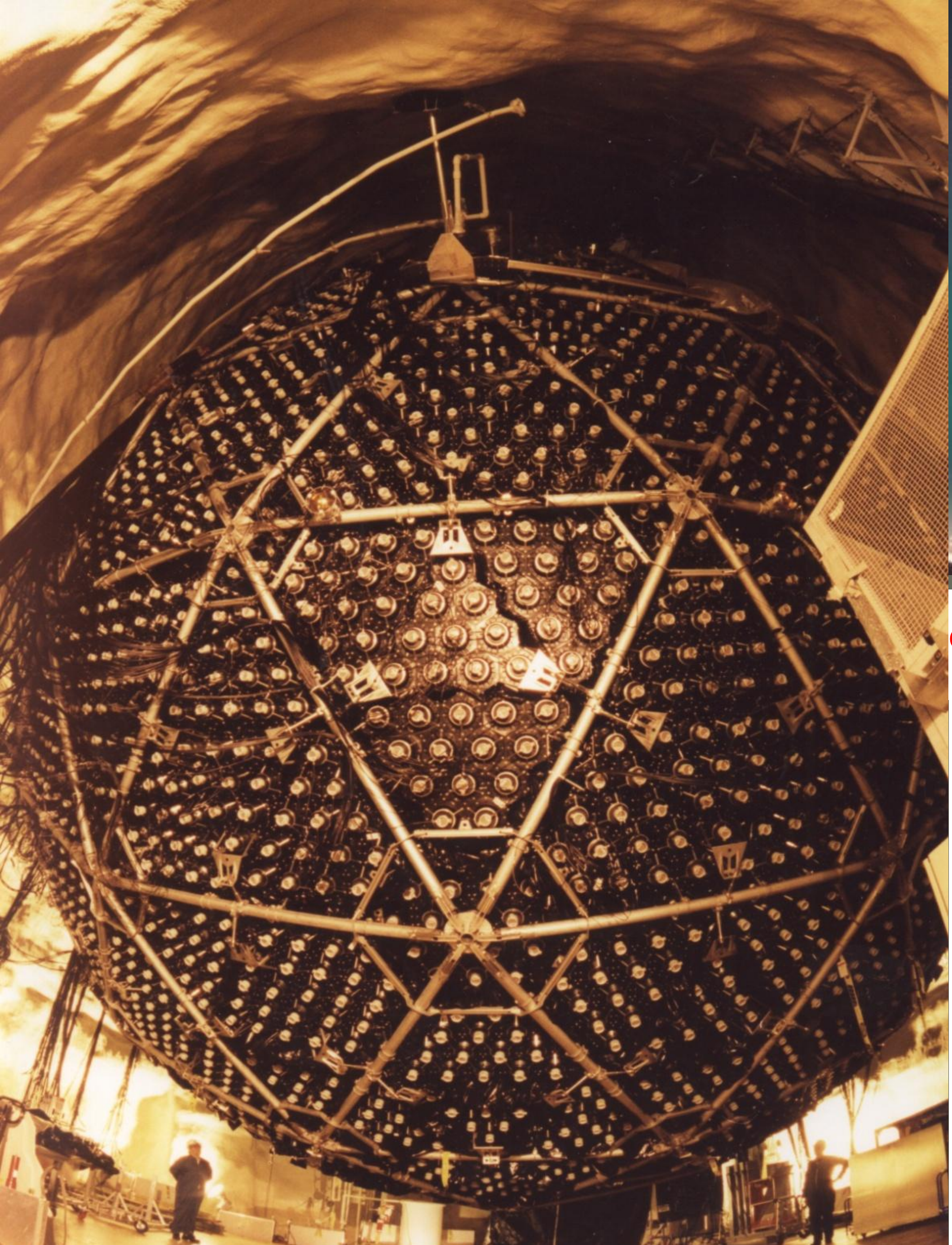
April 25, 2007 Philadelphia

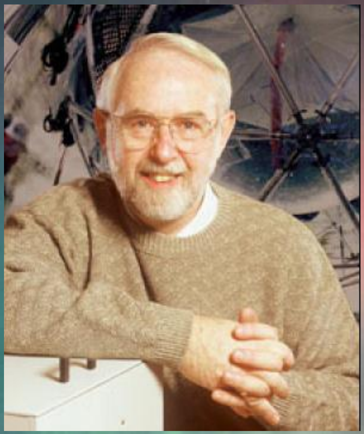
スーパーカミオカンデ
Super-Kamiokande





Yoji Totsuka



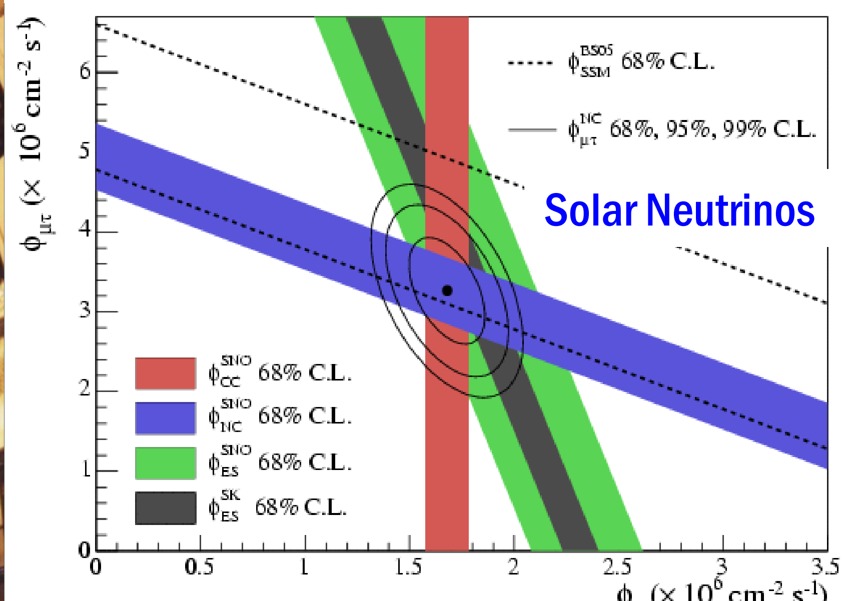


Fluxes (10^6 cm^{-2}s^{-1})

- ν_e : 1.76(11)
- $\nu_{\mu,\tau}$: 3.41(66)
- ν_{TOTAL} : 5.09(64)
- ν_{SSM} : 5.05

Art McDonald

$$\Phi(\nu_e) < \Phi(\nu_e + \nu_\mu + \nu_\tau) \approx \Phi(SSM)$$



Plan for Today's Talk

- Focus on the role of atmospheric neutrinos in revealing neutrino oscillations.
- Tell the story of large water Cherenkov detectors and why we built them.
- Give details of the initial discovery of neutrino oscillations and the current data.
- Present additional checks and confirmations.
- Preview the future for precision measurements in neutrino physics.

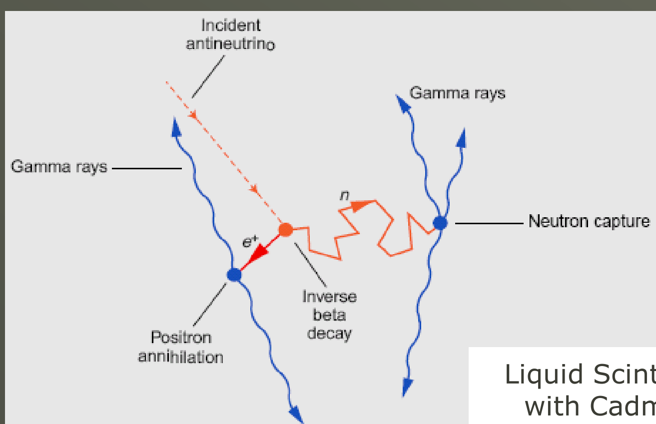
I'll start with some historical milestones ...

Fred Reines Clyde Cowan

Discovery of the Free Neutrino, 1956

"Project Poltergeist"
Hanford and Savannah River Reactors

$$\bar{\upsilon} + p \rightarrow n + e^{+}$$

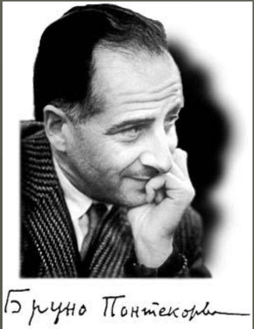


Liquid Scintillator with Cadmium

Phys. Rev. Lett. 92:330 (1953)
Science 124(3201):103 (1956) "… A Confirmation"
Phys. Rev. 117(1) :159 (1960)

Oscillations and Neutrino Flavor

Bruno Pontecorvo first suggested the possibility of neutrino oscillations if they had a small mass. Since only one neutrino was known, he was thinking that analogous to $K^0 - \bar{K}^0$ mixing:



$$\upsilon \leftrightarrow \bar{\upsilon}$$

J.Exp.Theor.Phys. <u>33</u> 549 (1957)
J.Exp.Theor.Phys. <u>34</u> 247 (1957)

In 1962, Lederman, Schwartz, Steinberger, *et al.* published evidence for the muon neutrino the their BNL/AGS experiment.

Neutrinos from pion decays make muons but not electrons. This could not be the same neutrino of nuclear beta decay that Reines and Cowan had seen. $\pi \rightarrow \mu + (\nu / \bar{\nu})$ $\nu_\mu \neq \nu_e$

Z. Maki, M. Nakagawa, S. Sakata, "Remarks on the unified model of elementary particles", *Prog.Theor.Phys.*, <u>28</u>, 870 (1962).

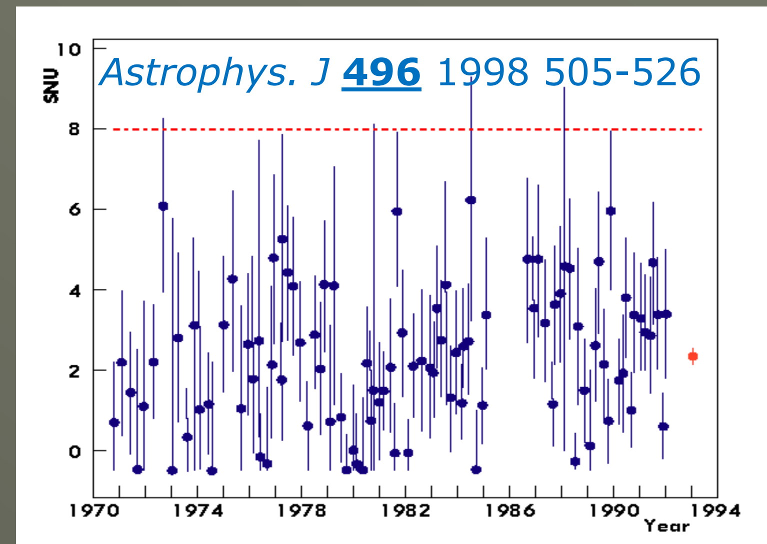
Late 1960's

Neutrinos From the Sun

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

100,000 gals C_2Cl_4

Davis and Bahcall in Homestake Mine



Ray Davis builds the Chlorine detector in Homestake Mine.

John Bahcall generates the Standard Solar Model with solar ν flux predictions.

V. Gribov and B. Pontecorvo, *Phys.Lett.* 28B 463 (1969). Suggested that Davis measurement could be explained by neutrino flavor oscillations.

$$\frac{R(\text{Measured})}{R(\text{Predicted})} = 0.34 \pm 0.03(\text{exp}) \pm 0.05(\text{th})$$

First evidence for neutrinos coming from the Sun.

First evidence for a deficit in the solar neutrino flux.

We have a Solar Neutrino Problem

$p+N \rightarrow \pi\text{'s and } K\text{'s}$

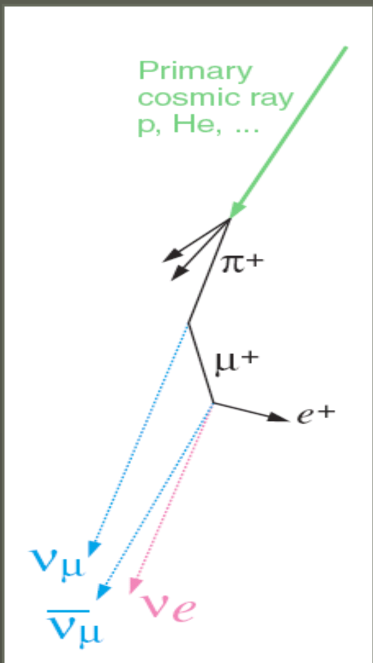
$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$

$K^{\pm} \rightarrow \mu^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu})$

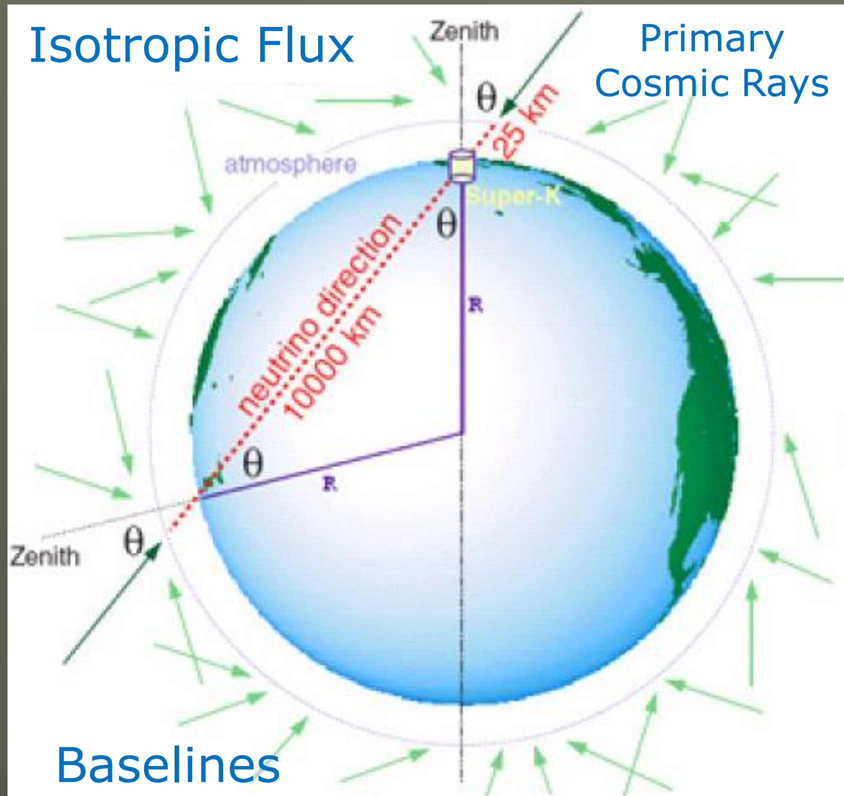
$\mu^{+} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$

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

Atmospheric Neutrinos

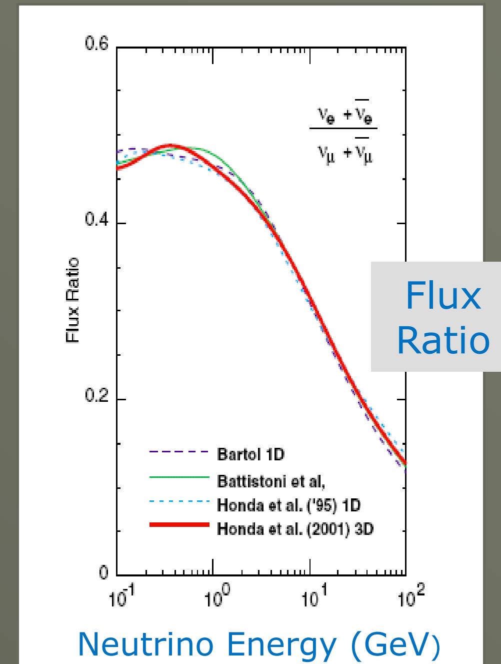


20 km



13,000 km

Gaisser and Honda, Ann.Rev.Nuc.Part.Sci.52(2002)



Flux Ratio of ν_μ to ν_e

- $\Phi(\nu_\mu)/\Phi(\nu_e) \sim 2$ below a few GeV
- predicted to ~ 5% over wide range

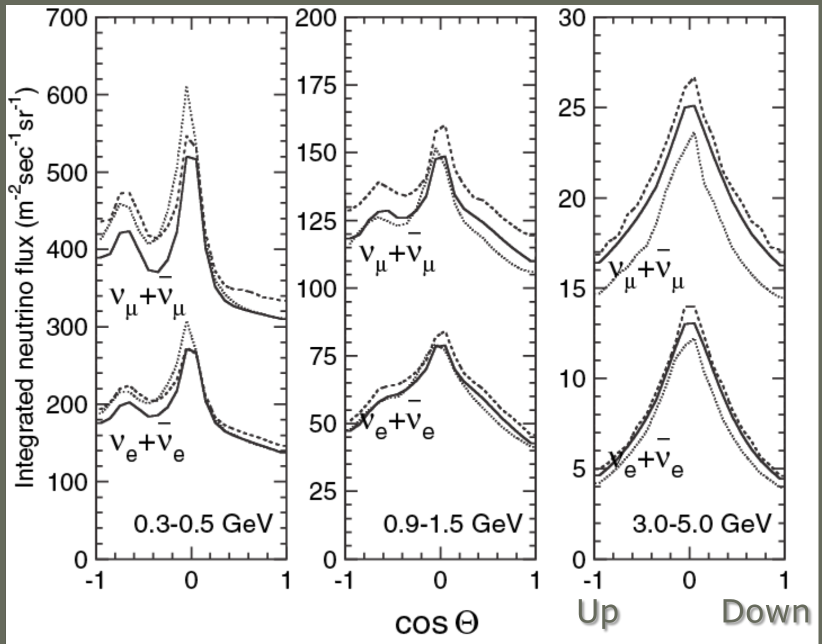
$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} = 2$$

2:1 Flavor Ratio

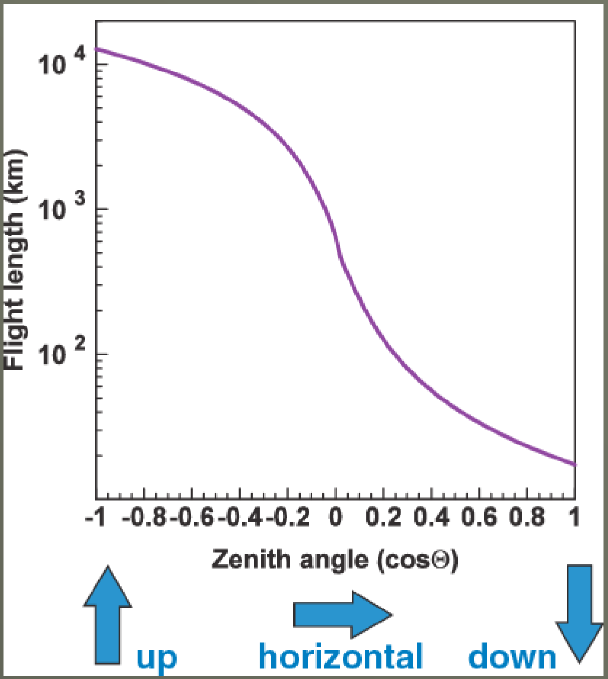
The absolute flux is uncertain by 10 – 20 %, but the flux ratio of ν_μ to ν_e is predicted to ~5% over a wide range of neutrino energy.

Atmospheric Neutrinos

Flux Characteristics



Pathlength Characteristics



Up-Down Symmetric E_ν > few GeV

Up – Down Asymmetry

$$A \equiv \frac{(U-D)}{(U+D)}$$

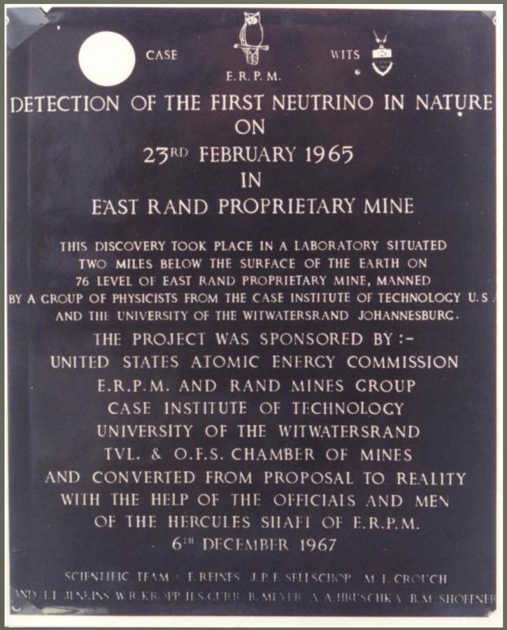
$$R \equiv \frac{\left(\frac{\upsilon_\mu + \bar{\upsilon}_\mu}{\upsilon_e + \bar{\upsilon}_e}\right)_{Measured}}{\left(\frac{\upsilon_\mu + \bar{\upsilon}_\mu}{\upsilon_e + \bar{\upsilon}_e}\right)_{Calculated}}$$

Up – Down Event #s

$$\frac{\text{Up}}{\text{Down}} = 1$$

if symmetric

Neutrinos From Earth's Atmosphere



2 Miles Deep

The first atmospheric neutrinos were detected in the mid-1960's. This is the Reines experiment in the East Rand Proprietary Mine in South Africa.

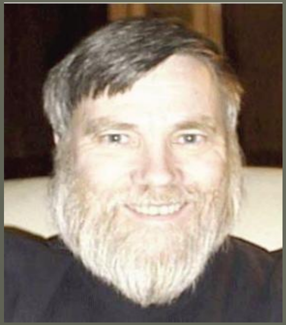
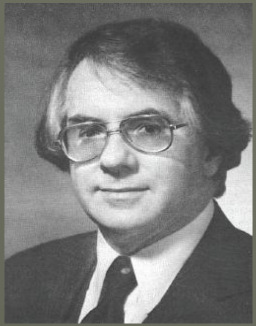
Another Japan-India experiment at the Kolar Gold Fields Mine also claims to have been first.

Bill Kropp
has detected more atmospheric neutrinos than any other person?

SA+IMB+SK

The 1970's

Grand Unified Theories ...

A group of theorists H. Georgi, S. Glashow, J. Pati, A. Salam and Others ...

Grand Unification Theory called SU(5) $p \rightarrow e^{+}\pi^{0}$

Proton Lifetime predicted to be $\sim 10^{29 \pm 1.7}$ years

Large H_2O Cherenkov detectors are born:

Kamioka Nucleon Decay Experiment = KamiokaNDE

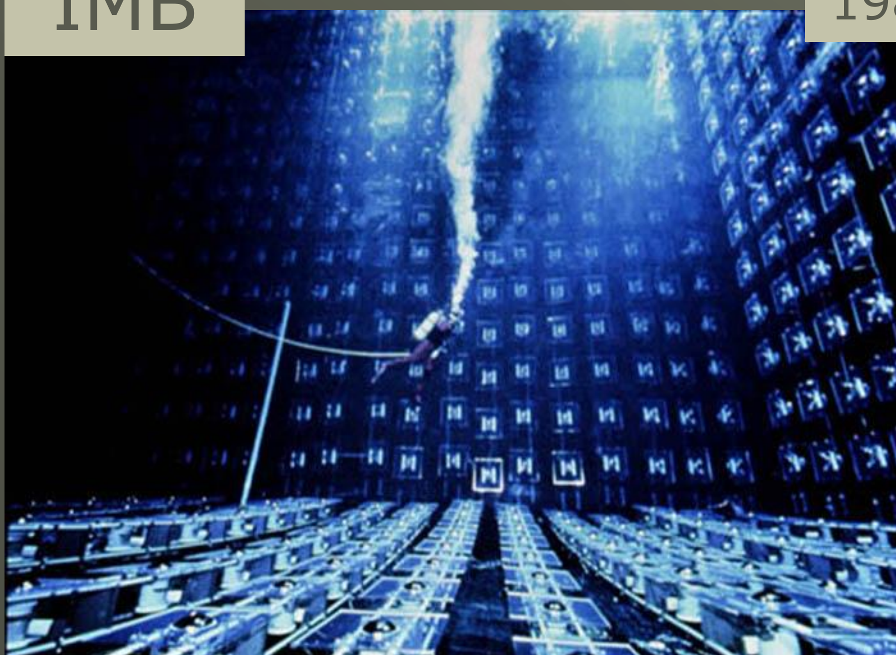
Irvine, Michigan, Brookhaven = IMB

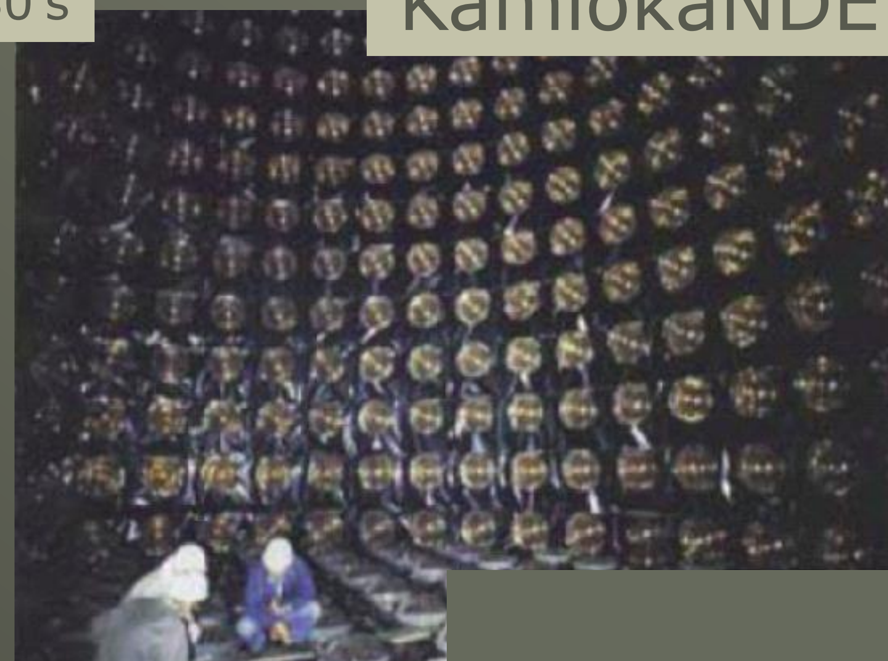
Several groups around the world knew that this lifetime could be measured by watching a few thousand tons of matter for a few years. They started building various kinds of detectors in underground mines and tunnels.

IMB

1980’s

KamiokaNDE





Begins era of large water Cherenkov detectors in deep underground caverns.

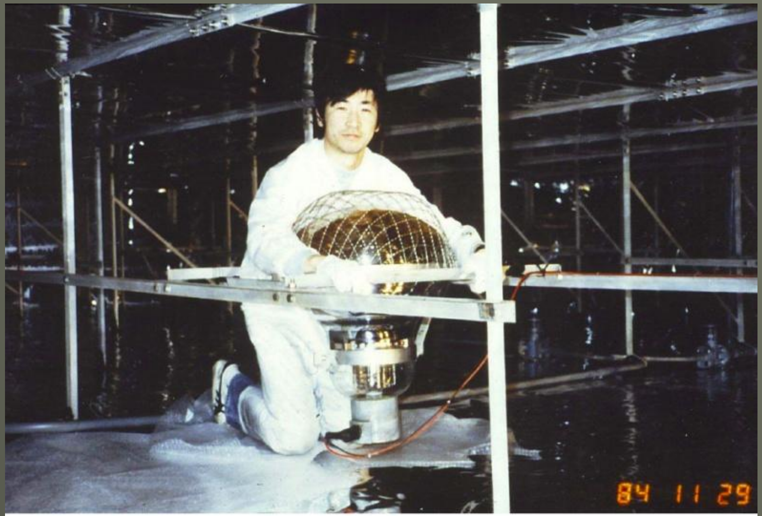
Water Cherenkov Detector Fact Sheets

IMB

- 8 kton total mass
- 3.3 kton fiducial mass
- 2018 5″ PMTs (IMB-I), 8″ PMTs + WLS plates (IMB-III)
- 2% then ~8% photocathode
- Electronics records Q and T
- Data taking 1982 - 1991

Kamiokande

- 3 kton total mass
- 1 kton fiducial mass
- 1000 50 cm diameter PMTs
- 20% photocathode coverage
- Electronics records Q (Kam-I), then Q and T (Kam-II)
- Data taking 1983 – 1994

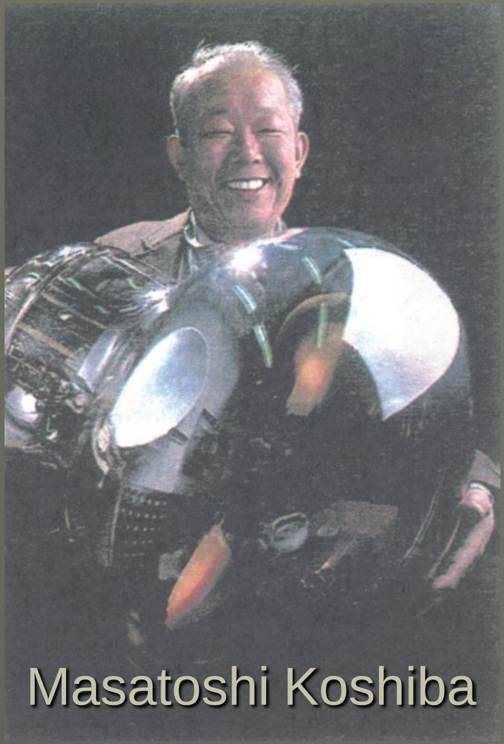


Installation of bottom anti-counters.

Takaaki Kajita Kamiokande-II

Large Water Cherenkov Detectors required good light collection: Large PMTs with good timing, good QE at 480 nm, strong glass housings.

The initial large hemispherical PMT, 50 cm diameter, was developed by ICRR, U. of Tokyo and Hamamatsu Photonics K.K.



IMB – Kamiokande-I difference boils down to small light collection with T + Q electronics and large light collection and with Q electronics only.

IMB Version

Our Fiducial Mass

Theirs

Michigan graduate students
Eric Shumard and Hye-Sook Park

Goal was Proton Decay

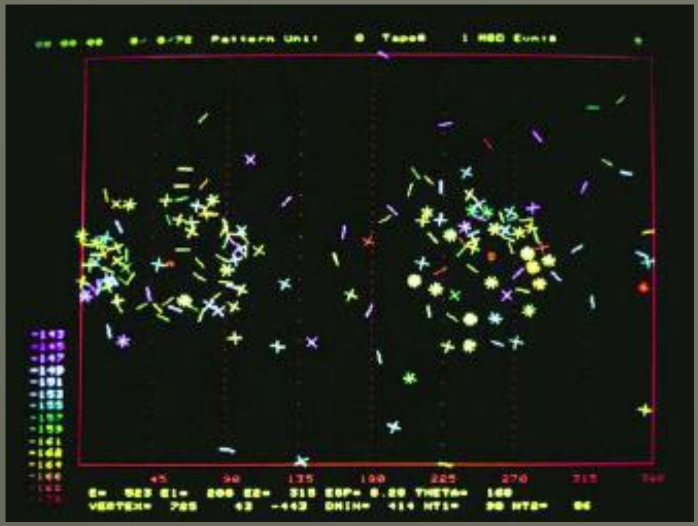
SU(5) ??

$p \rightarrow e^{+}\pi^{0}$

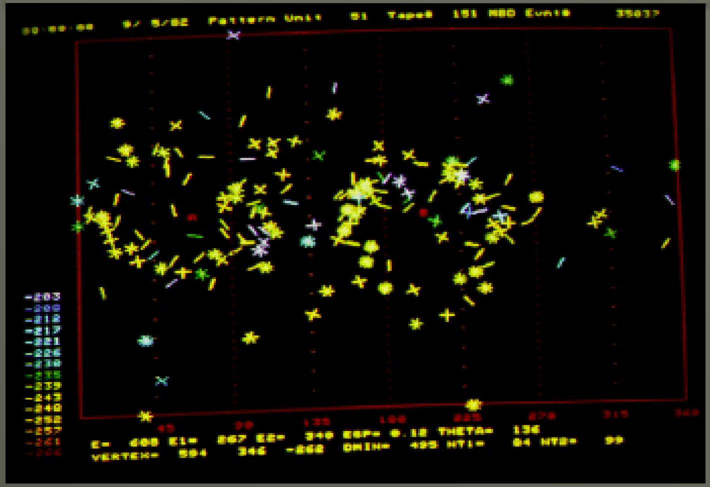
For this decay mode, two nearly back-to-back showering rings are expected with no associated muon decays.

IMB's two best examples are shown.

No proton decay events are found.



Top event has a muon decay.



Event has too much energy.
Not enough opening angle.

Proton Lifetime Exceeds 10^{31} Years

VOLUME 51, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1983

Search for Proton Decay into $e^+\pi^0$

R. M. Bionta, G. Blewitt, C. B. Bratton, B. G. Cortez,[a] S. Errede, G. W. Forster,[a] W. Gajewski, M. Goldhaber, J. Greenberg, T. J. Haines, T. W. Jones, D. Kielczewska,[b] W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, P. V. Ramana Murthy,[c] H. S. Park, F. Reines, J. Schultz, E. Shumard, D. Sinclair, D. W. Smith,[d] H. W. Sobel, J. L. Stone, L. R. Sulak, R. Svoboda, J. C. van der Velde, and C. Wuest

The University of California at Irvine, Irvine, California 92717, and The University of Michigan, Ann Arbor, Michigan 48109, and Brookhaven National Laboratory, Upton, New York 11973, and California Institute of Technology, Pasadena, California 91125, and Cleveland State University, Cleveland, Ohio 44115, and The University of Hawaii, Honolulu, Hawaii 96822, and University College, London WC1E 6BT, United Kingdom

(Received 13 April 1983)

Observations were made 1570 met
metric-ton water Cherenkov detect
with the decay $p \to e^+\pi^0$ were found i
that the limit on the lifetime for bou
ratio is $\tau/B > 6.5 \times 10^{31}$ yr; for free
dence). Observed cosmic-ray muor

PACS numbers: 13.30.Eg, 11.30.Ly

IMB

SU(5)

No Proton Decay

Kamiokande

Journal of the Physical Society of Japan
Vol. 54, No. 9, September, 1985, pp. 3213–3216

Search for Nucleon Decay into Charged Lepton+Mesons

Katsushi ARISAKA, Takaaki KAJITA, Masatoshi KOSHIBA, Masayuki NAKAHATA, Yuichi OYAMA, Atsuto SUZUKI, Masato TAKITA, Yoji TOTSUKA, Tadashi KIFUNE,† Teruhiro SUDA,† Kasuke TAKAHASHI†† and Kazumasa MIYANO†††

Department of Physics and ICEPP, University of Tokyo, Tokyo 113
†Institute for Cosmic Ray Research, University of Tokyo, Tokyo 188
††KEK, National Laboratory for High Energy Physics, Ibaraki 305
†††Department of Physics, University of Niigata, Niigata 950–21

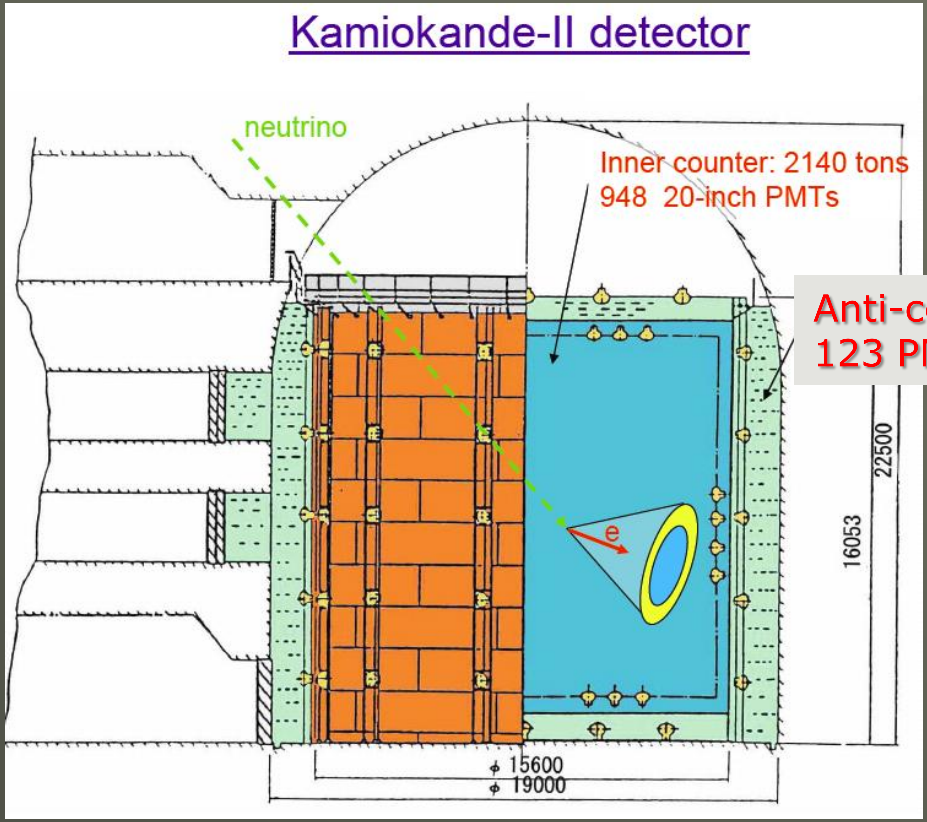
(Received July 19, 1985)

With a 3000 ton water Cerenkov detector operated 2700 m.w.e. underground, 103 fully contained events were observed during a live time of 343 days. Most of the events are well interpreted as due to ν interactions. Four multi-ring events survive after applying criteria for nucleon decay. The lower limits on τ/B obtained from these data exceed 10^{31} yr (90% C.L.) for most of the possible decay modes.

What to do now?

Kamiokande Reconfigures

An Innovation for Water Cherenkov Detectors



Anti-counter
123 PMTs

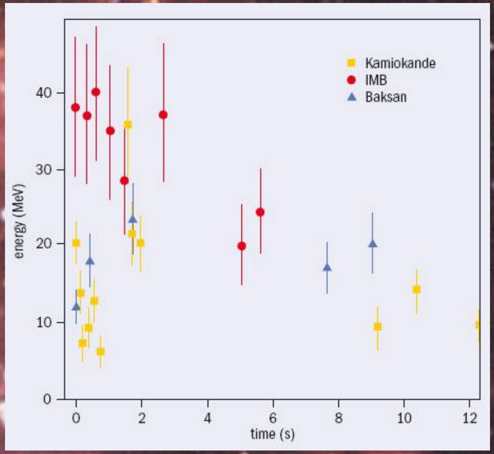
- U. Penn. group joins Kam-II
- Timing added to Inner PMTs
- Lowers energy threshold
- Outer PMTs for anti-counter

Bruce Cortez   Al Mann

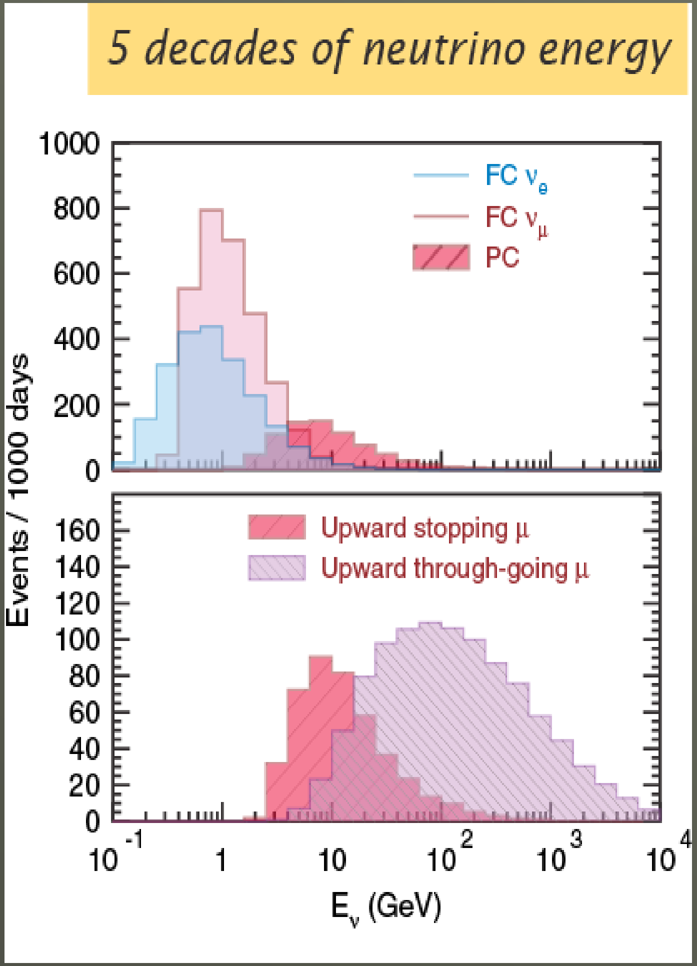
Feb. 1984 KamiokaNDE-II started.

$E_\nu > 7$ MeV
Solar Neutrinos
Supernovae Neutrinos
+ Atmospheric Neutrinos

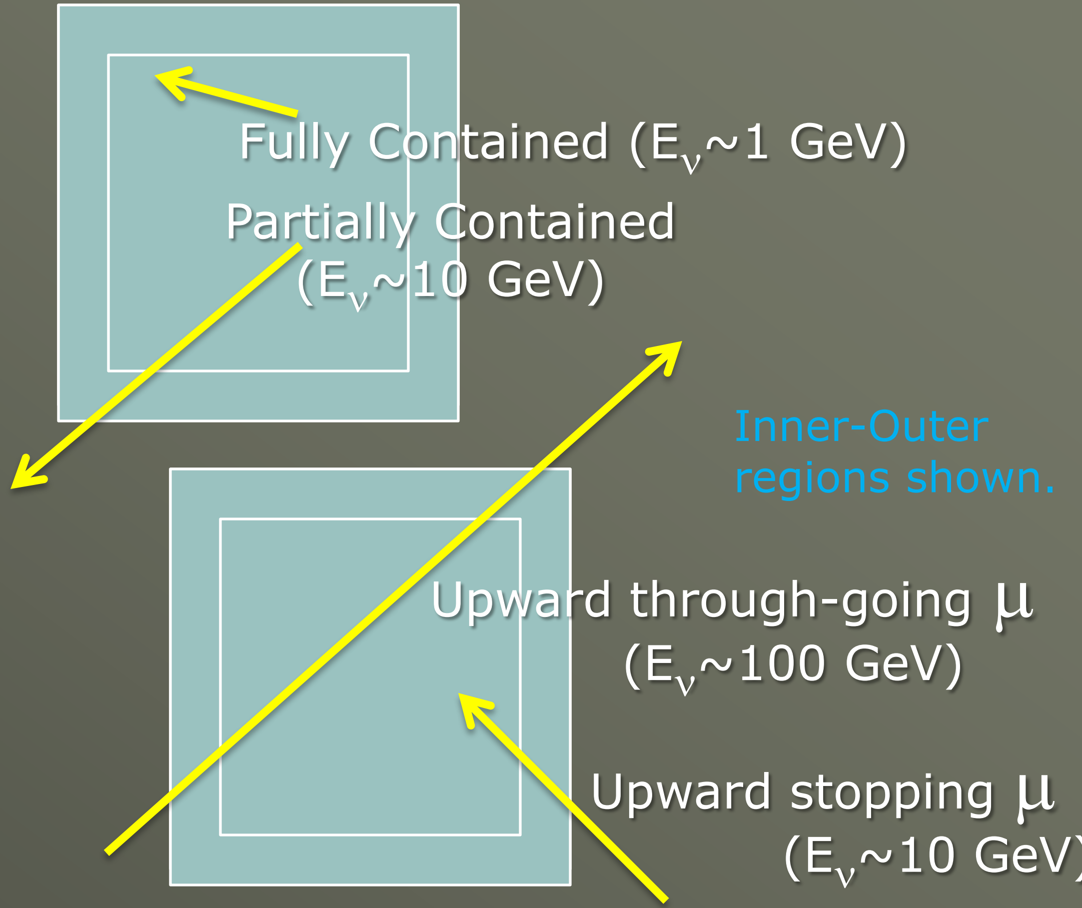
Supernova in the Large Magellanic Cloud, February 23, 1987
SN1987A. Kamiokande (11) and IMB (8) observe burst of 19 neutrinos a few hours prior to the reported optical signal.



Atmospheric Neutrinos Energy Characteristics



Event Type Terminology

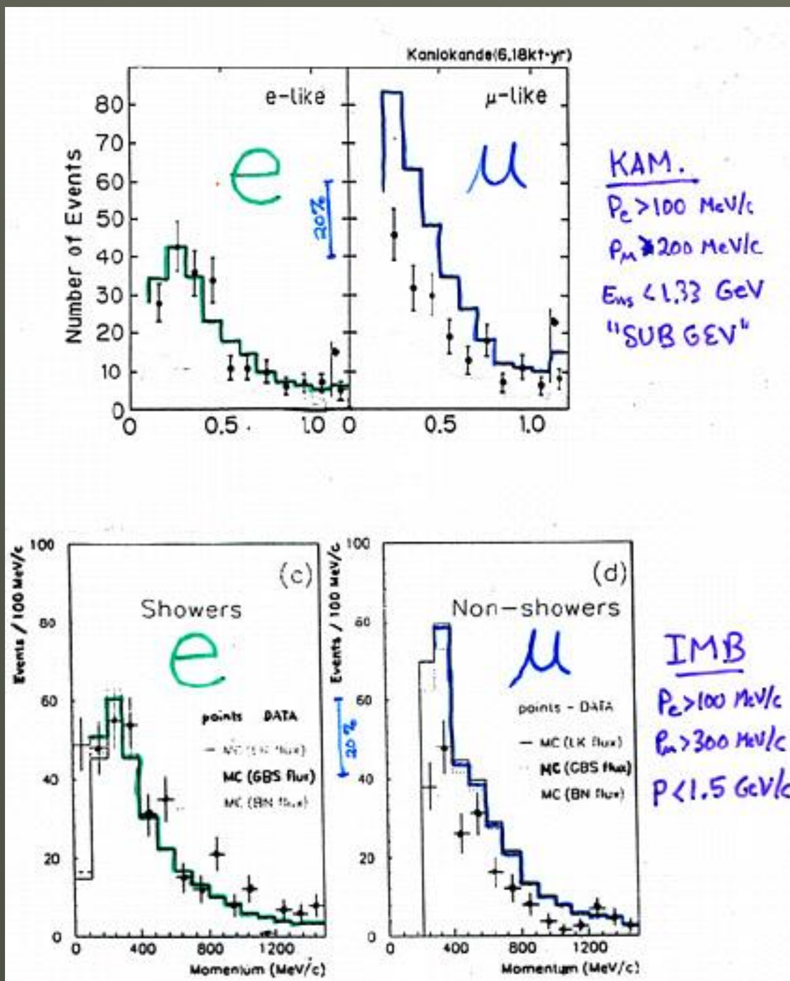


Subdivide the data into bins of Sub-GeV or Multi-GeV FC; e-like or mu-like, partially contained, upgoing muons, upgoing-stopping ...

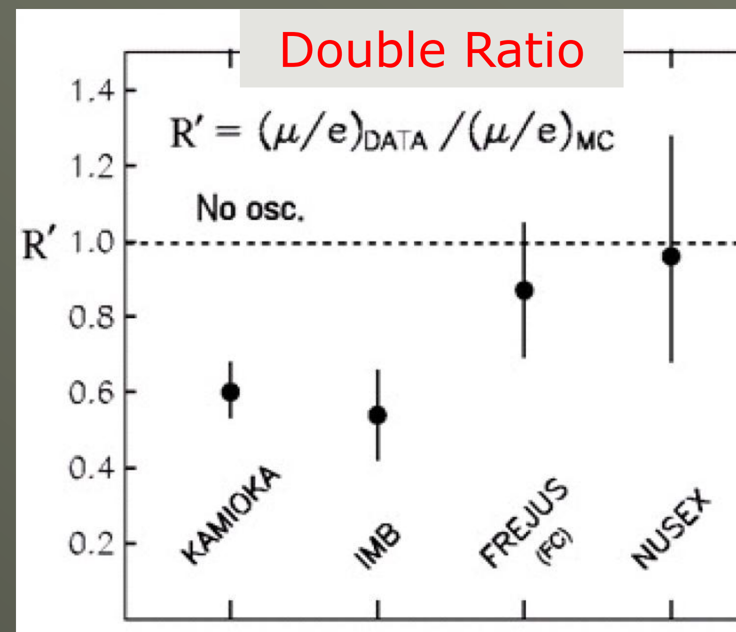
Mid-1980s

An Atmospheric Neutrino Puzzle

Comparison of Kamiokande and IMB Sub-GeV Data



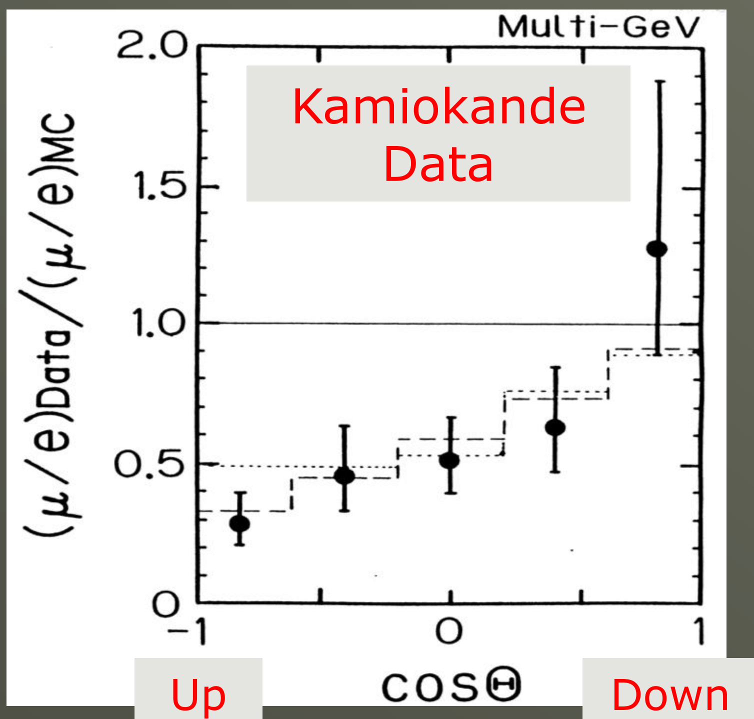
The double ratio is used to cancel uncertainties in the atmospheric neutrino flux and cross-sections. If measured and expected agree, then R = 1.



Water Cherenkov – Muon Deficit
Iron Trackers – No Deficit

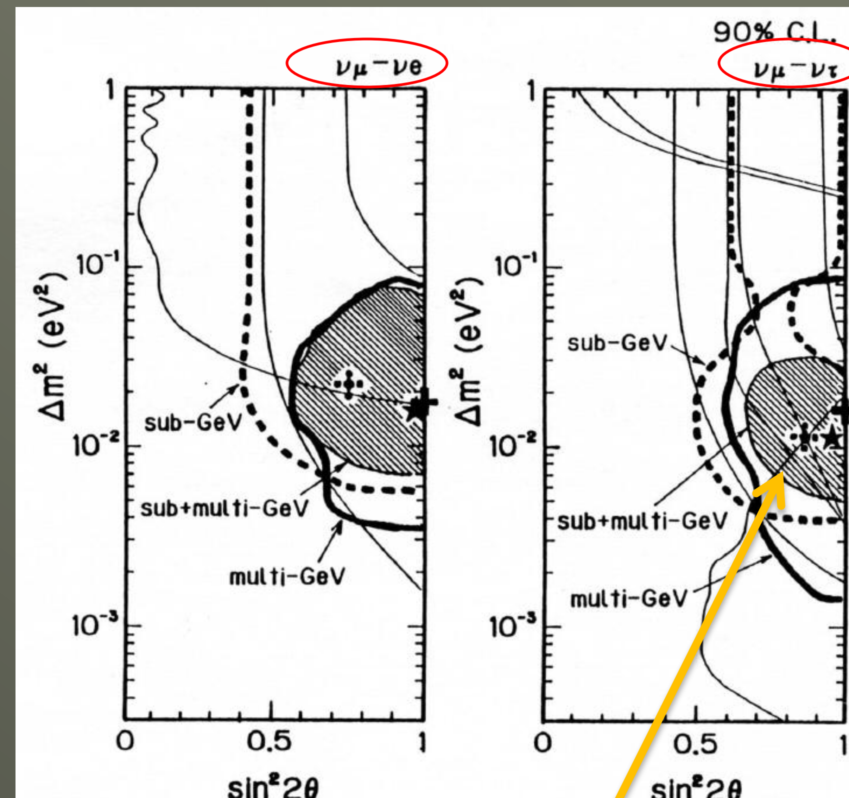
Kamiokande Allowed Regions

Using multi-GeV events including partially contained, Kamiokande-II finds a zenith angle variation of the μ/e double ratio at high-energy.



Outer-detector region of Kam-II allows PC events.

$\nu_\mu \rightarrow \nu_e$ oscillations are ruled out by the Chooz Experiment. (Not Shown)



Best Fit for $\nu_\mu \rightarrow \nu_\tau$

$\Delta m^2 = 1.6 \times 10^{-2}$ eV^2

$\sin^2 2\theta = 1.0$

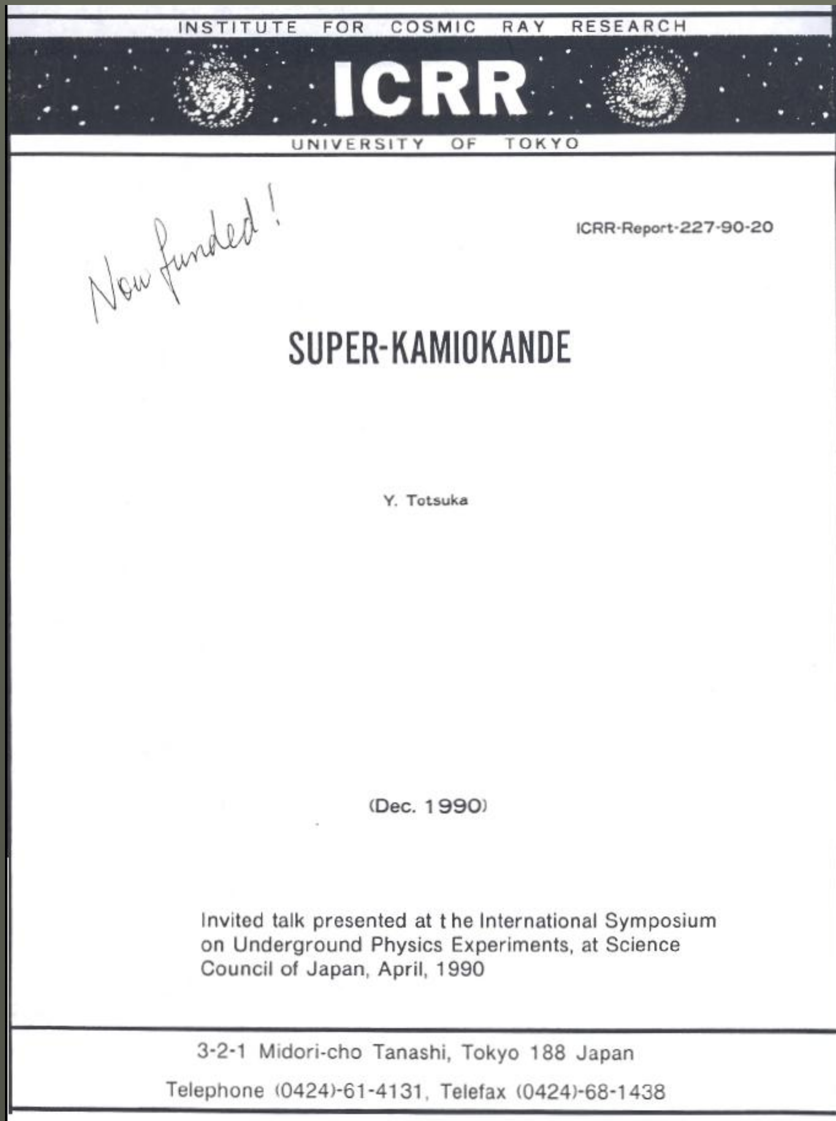
Two Major Puzzles with Neutrinos ~1990

Solar neutrino flux measured by multiple experiments is in disagreement with expectations of the Standard Solar Model.

Atmospheric muon neutrino flux measured by multiple experiments is in disagreement with calculations AND Kamiokande sees strong evidence for an up–down asymmetry in the double ratio of muon/electron neutrinos.

Low energy threshold and active anti-counter have become important to study these effects. IMB's small PMTs were not competitive. What to do?

Spring 1991, IMB tank developed a leak that caused much damage to the detector. IMB had to be stopped. The 2000 PMTs were recovered.



INSTITUTE FOR COSMIC RAY RESEARCH

ICRR

UNIVERSITY OF TOKYO

Now funded!

ICRR-Report-227-90-20

SUPER-KAMIOKANDE

Y. Totsuka

(Dec. 1990)

Invited talk presented at the International Symposium on Underground Physics Experiments, at Science Council of Japan, April, 1990

3-2-1 Midori-cho Tanashi, Tokyo 188 Japan

Telephone (0424)-61-4131, Telefax (0424)-68-1438

IMB group had >2000 PMTs and WLS plates ready for water deployment, HV, electronics, etc.

"Super-Kamiokande project has changed greatly since neutrinos from the Large Magellanic Clouds were successfully detected."

"Reliable data on solar neutrinos has emerged ... posed a serious problem called the solar neutrino problem."

"It is now widely believed that it could be solved by finite neutrino masses ..."

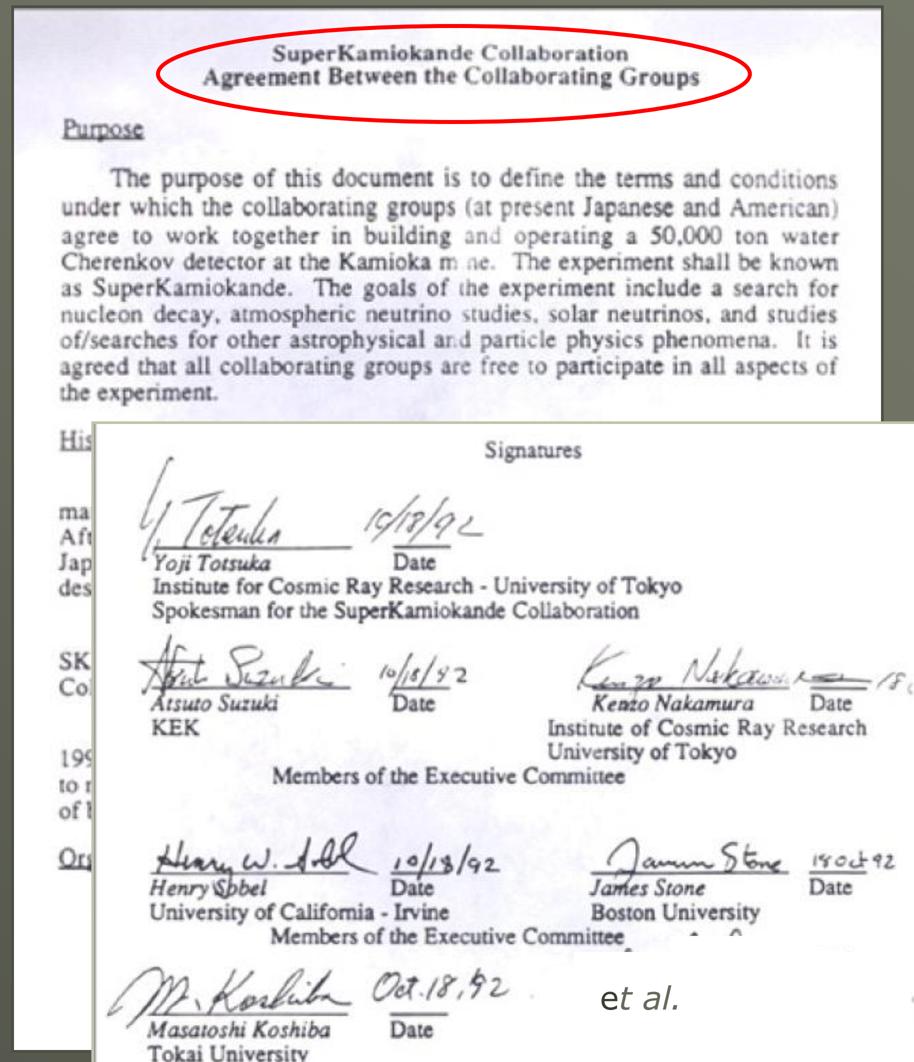
"The anti-counter layers that surround the sensitive volume of the detector were found essential to eliminate backgrounds (γ's and neutrons) for low-energy neutrinos."

Y. Totsuka

IMB Group Joins Super-Kamiokande

At ICRR in spring of 1992, our agreement to work together on Super-Kamiokande is celebrated. The IMB group would build the outer detector.

Collaboration Agreement Signed October 18, 1992 in Takayama



SuperKamiokande Collaboration
Agreement Between the Collaborating Groups

Purpose

The purpose of this document is to define the terms and conditions under which the collaborating groups (at present Japanese and American) agree to work together in building and operating a 50,000 ton water Cherenkov detector at the Kamioka mine. The experiment shall be known as SuperKamiokande. The goals of the experiment include a search for nucleon decay, atmospheric neutrino studies, solar neutrinos, and studies of/searches for other astrophysical and particle physics phenomena. It is agreed that all collaborating groups are free to participate in all aspects of the experiment.

Signatures

Yoji Totsuka — Date
Institute for Cosmic Ray Research - University of Tokyo
Spokesman for the SuperKamiokande Collaboration

Atsuto Suzuki — Date
KEK

Kenzo Nakamura — Date
Institute of Cosmic Ray Research
University of Tokyo

Members of the Executive Committee

Henry Sobel — Date
University of California - Irvine

James Stone — Date
Boston University

Members of the Executive Committee

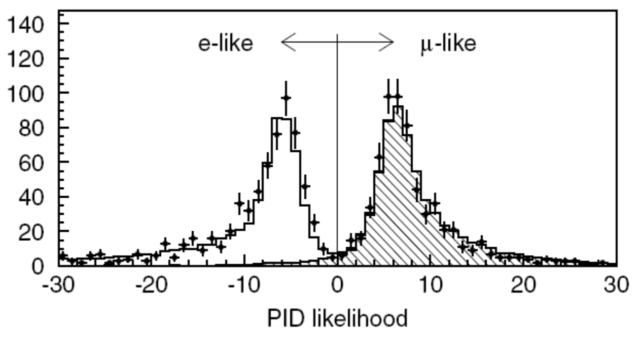
Masatoshi Koshiba — Date
Tokai University

et al.

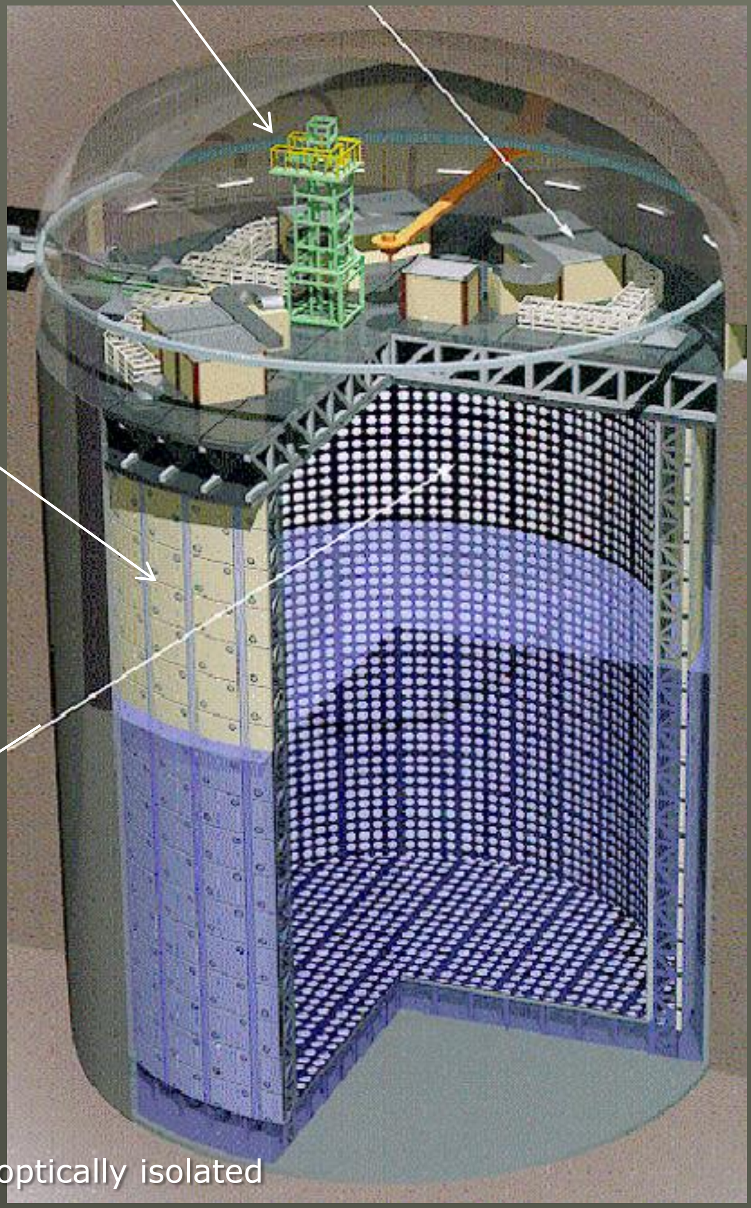
The first project performed together as a Collaboration was the KEK Beam Test

1993 - 95

Using KEK PS charged particle beams, these test runs checked the particle identification algorithms of the 50 cm PMTs used in Kamiokande and 8 inch PMTs used in IMB.



Particle ID methods for separating e-like and μ-like events verified.

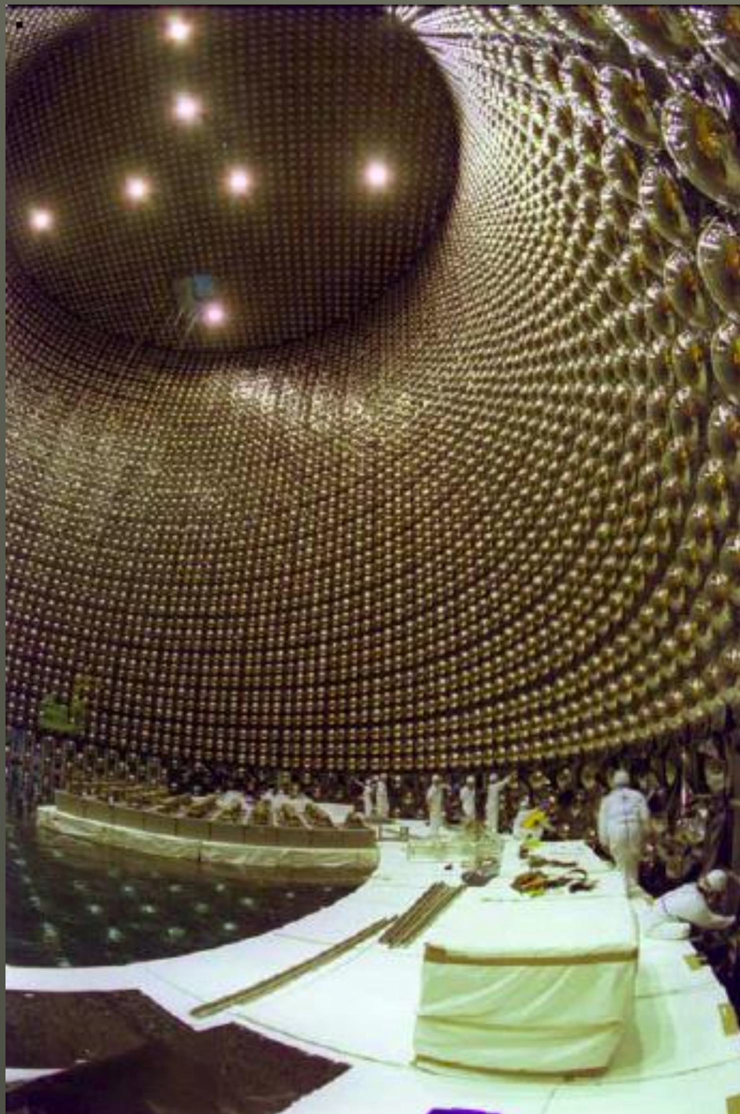


Super-Kamiokande Detector

41 m height x 39 m diameter
50,000 ton total mass
22,000 ton fiducial volume
11,146 50 cm PMTs Inner
1,885 20 cm PMTs Outer
2 ns timing resolution
40% photocathode coverage
1000 m minimum depth

4.5 MeV Trigger threshold
E Res. 16%/$E^{1/2}$ @ 10 MeV
Position ~50 cm @ 10 MeV
Angular ~30° @10 MeV
Muon decay ~95%
Electron – Muon ID ~99%

Inner Space – Outer Space



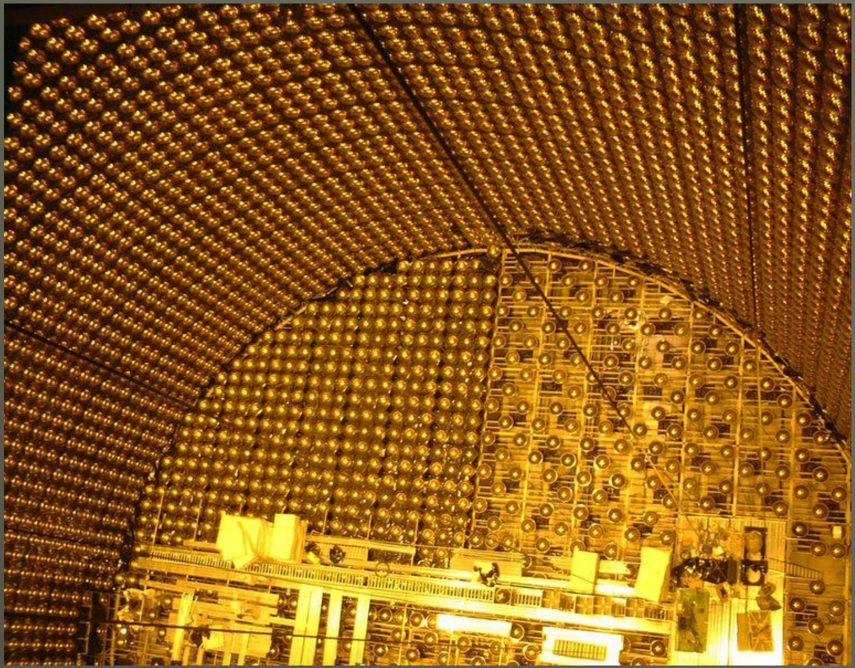
Super-K Inner Detector Construction

Looking up in the Super-K Outer Detector

Hank Sobel

Current Spokesman Yoichiro Suzuki greeting the Emperor and Empress of Japan.

Construction Work in the Super-K Tank …



Physics Objectives of Super-Kamiokande

Search for Nucleon Decay

τ/BR > 10^{33} – 10^{34} years

Study Atmospheric Neutrino Interactions

> 3000 events/year

Measurement of the ^{8}B Solar Neutrino Flux

~15 events/day for E_ν > 5 MeV

Watch for Supernovae Neutrinos

> 7000 events for Type II SN @ 10 Kpc

Study Upward-going Muons

WIMP dark matter, Atmospheric ν's

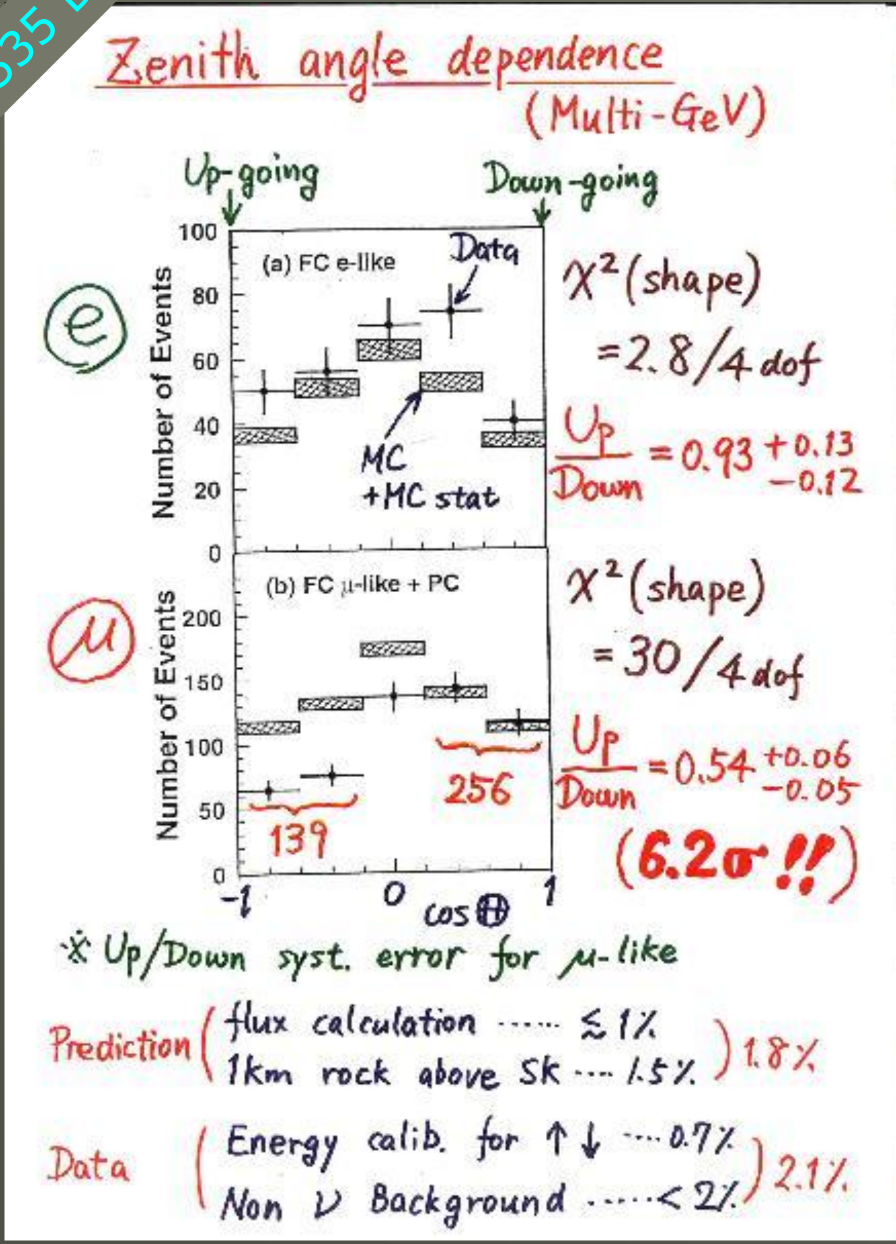
Studies of Long Baseline Neutrinos from KEK

~200 CC events w/10^{20} pot

Detector built, calibrated, operated, analyzed, many meetings etc. ...

1998 Announcement

535 Days



From Talk by T. Kajita
Neutrino '98
Takayama, Japan

Electron Neutrinos are as Expected

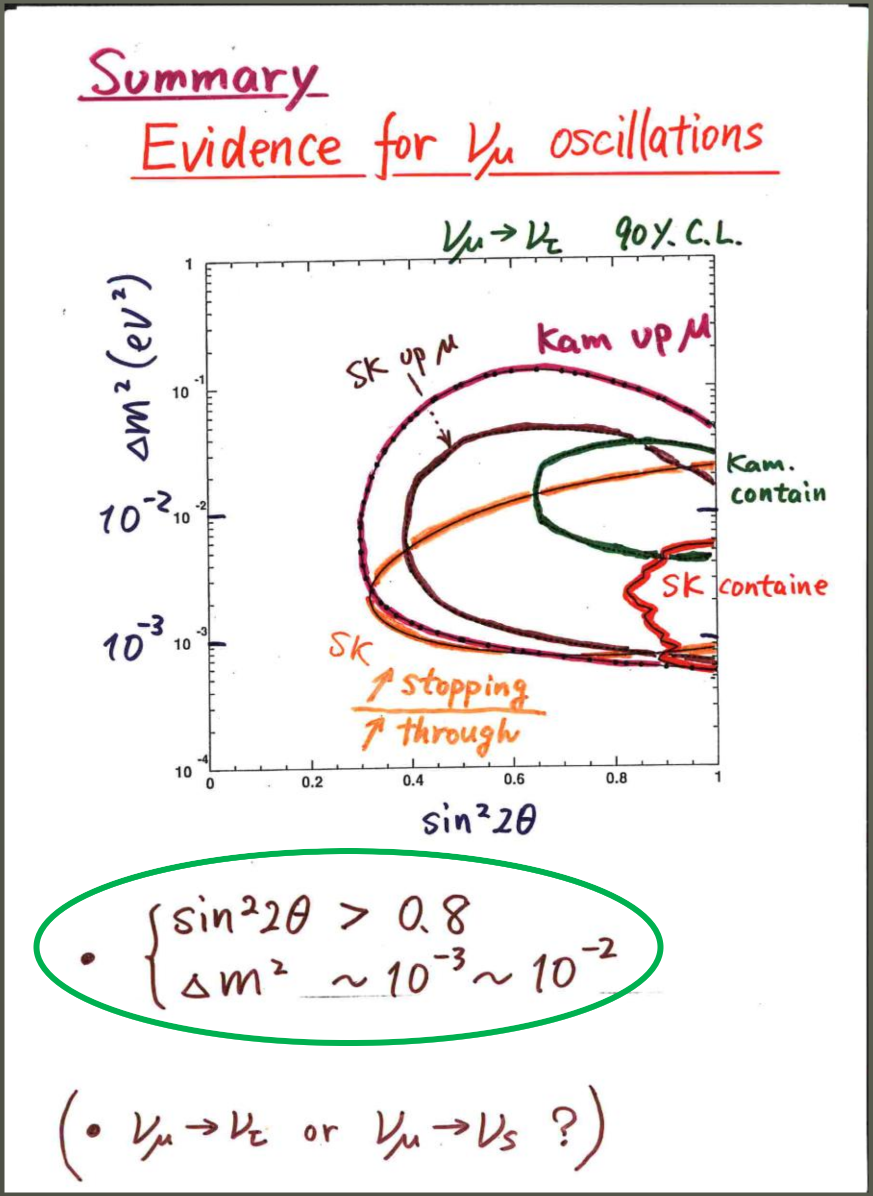
Up/Down Event Ratio

Muon Neutrinos Show Deficit from Other Side of Earth!

Strong Evidence that Neutrinos change from one flavor to another.

Neutrinos Have Mass

Evidence for ν_μ Oscillations



From Talk by T. Kajita
Neutrino '98
Takayama, Japan

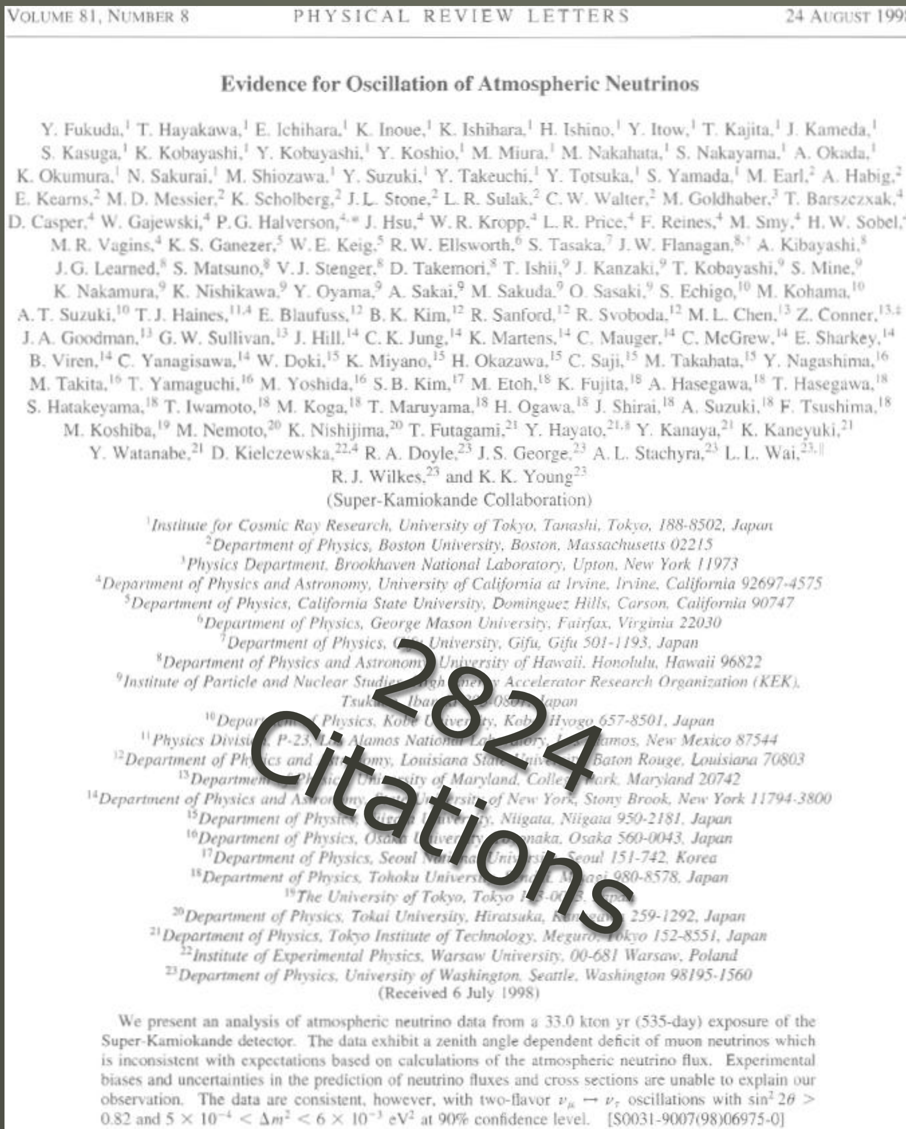
Super-K Up-muon zenith angle data confirms evidence.

Super-K Up-muon stopping to through going double ratio confirms evidence.

Kamiokande Up-muon zenith angle data consistent with evidence.

"Evidence for Oscillation of Atmospheric Neutrinos"

Phys.Rev.Lett.81:1562-1567,1998



VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

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(Received 6 July 1998)

We present an analysis of atmospheric neutrino data from a 33.0 kton yr (535-day) exposure of the Super-Kamiokande detector. The data exhibit a zenith angle dependent deficit of muon neutrinos which is inconsistent with expectations based on calculations of the atmospheric neutrino flux. Experimental biases and uncertainties in the prediction of neutrino fluxes and cross sections are unable to explain our observation. The data are consistent, however, with two-flavor $\nu_\mu \to \nu_\tau$ oscillations with $\sin^2 2\theta > 0.82$ and $5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3}$ eV^2 at 90% confidence level. [S0031-9007(98)06975-0]

2824 Citations

One of many front page articles in the newspapers of the world following Kajita's talk in Takayama in 1998.

This PRL is the most cited paper in experimental high energy physics as tracked by the SPIRES database.

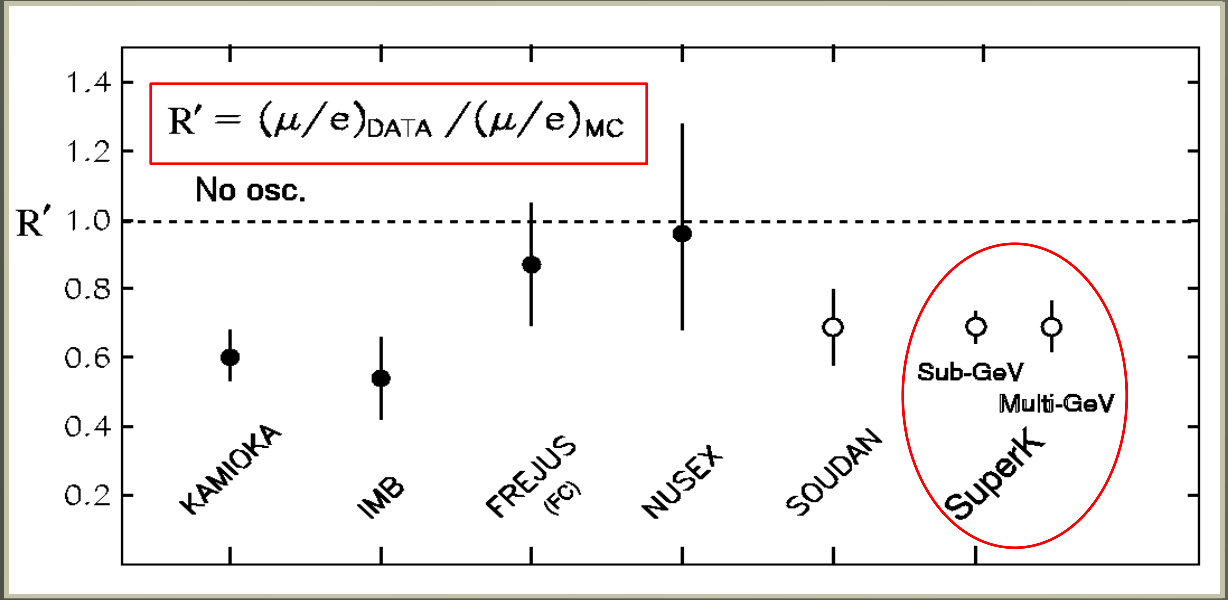
More evidence that it is oscillations:

The 1998 values of the double ratio from Super-Kamiokande are given:

Sub-GeV Data:	$R = 0.61 \pm 0.03(stat) \pm 0.05(sys)$
Multi-GeV Data:	$R = 0.66 \pm 0.06(stat) \pm 0.08(sys)$

*Phys.Lett.*B433, 9-18 (1998)

Soudan 2: $R = 0.68 \pm 0.12(total)$



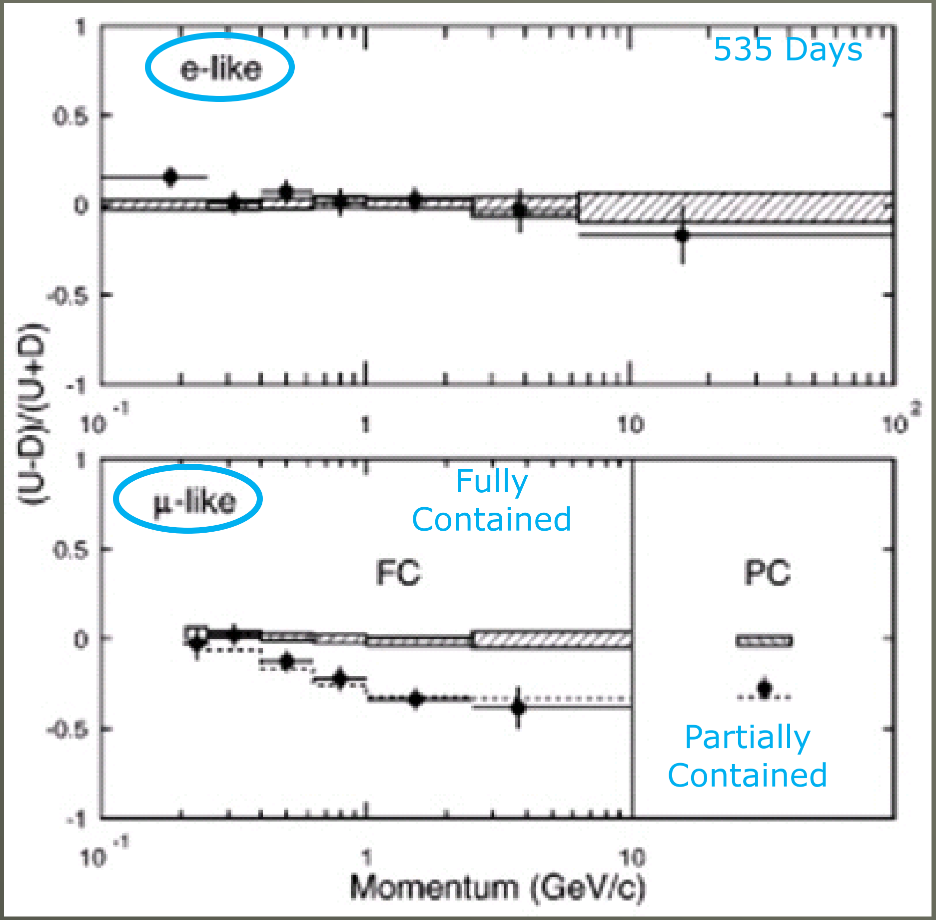
No Oscillations

5 Yes
2 No

Another way of looking:

The up – down asymmetry parameter, A, as a function of momentum is presented in the "evidence" paper: *Phys.Rev.Lett.*81, 1562-1567 (1998)

$$A \equiv \frac{(U-D)}{(U+D)}$$



Due to the isotropic nature of cosmic rays, A = 0, absent of oscillations.

Electron-like events agree with expectation (shaded) for no oscillations.

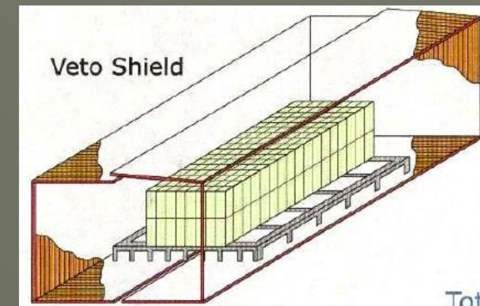
The strong suppression of upgoing muon-like events is consistent with oscillations (dotted line).

Deviation from zero > 6σ

MACRO and Soudan 2 Experiments

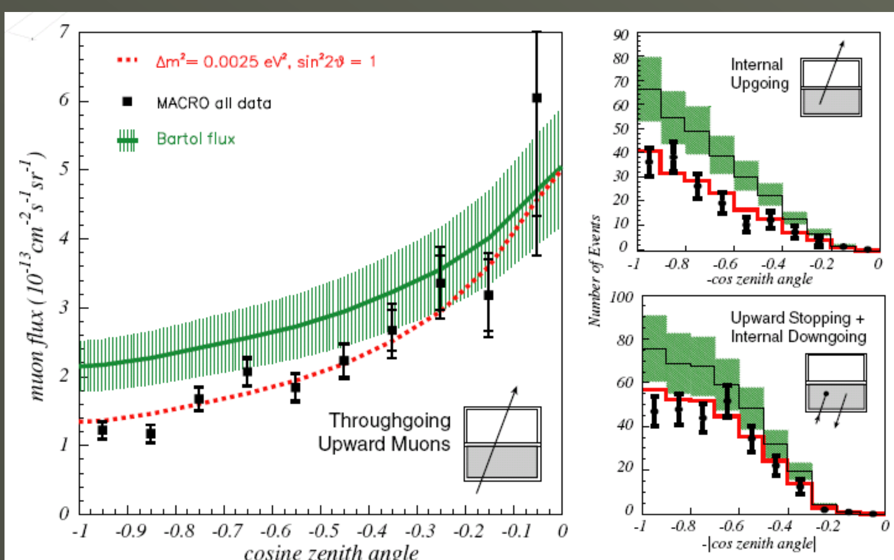
Confirmation

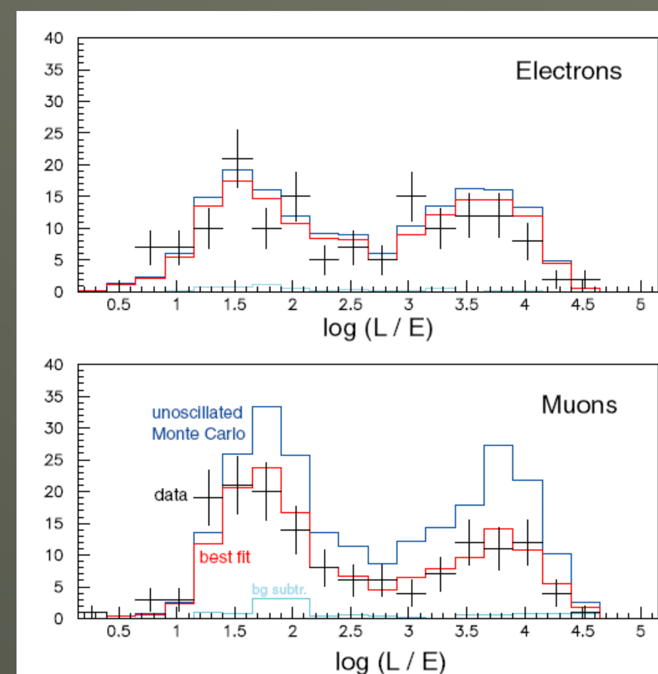
Very soon after the 1998 announcement, MACRO and Soudan groups reported results consistent with the Super-K oscillation parameters.



MACRO Experiment
Up-going muons

Soudan 2 Experiment
High resolution events





Super-Kamiokande Running Periods

K2K Run

SK-I 1996 – 2001

- 22.5 kton fiducial mass, 2 m from PMT plane
- 11,134 50-cm photomultiplier tubes inner detector
- 40% photocathode coverage of detector wall
- 1885 20-cm PMTs + WLS plates in outer detector

K2K Run

SK-II December 2002 – September 2005

- Recovered from November 12, 2001 PMT accident
- Inner detector PMTs reduced to half, now with FRP+Lucite shields
- 20% photocathode coverage of detector wall
- Outer detector fully restored

SK-III June 2006 – Now Running

- Full restoration of inner detector PMTs
- 40% photocathode coverage of detector wall

2009

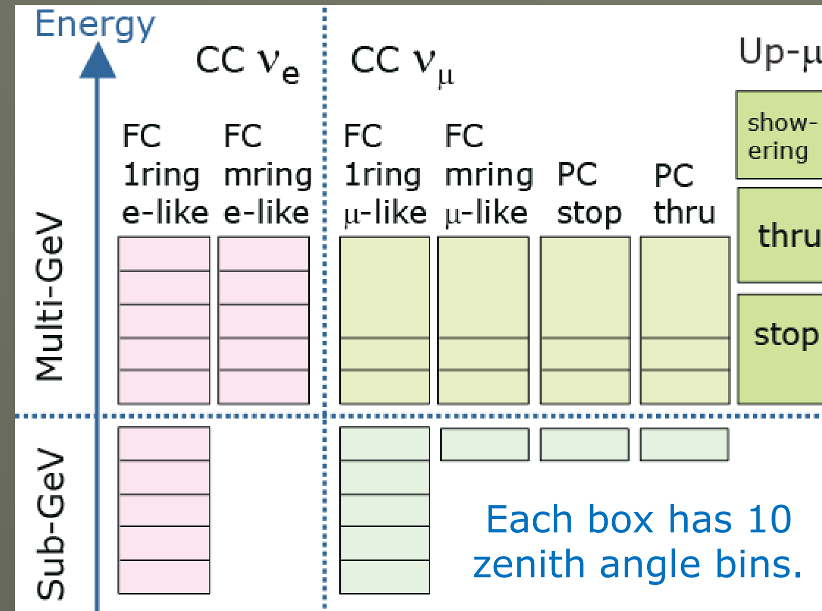
- Start running with T2K long baseline beam from Tokai

Recent Super-K Atmospheric Neutrino Data

For a two flavor oscillation analysis, the survival probability is given by:

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

We study Δm^2 and $\sin^2 2\theta$ by binning the real and simulated data in *cos* θ and *p*, then minimizing χ^2 to find the best fit values.



380 (p,θ) bins and 70 systematic terms used in fit.

The Fit

number of p, Θ bins

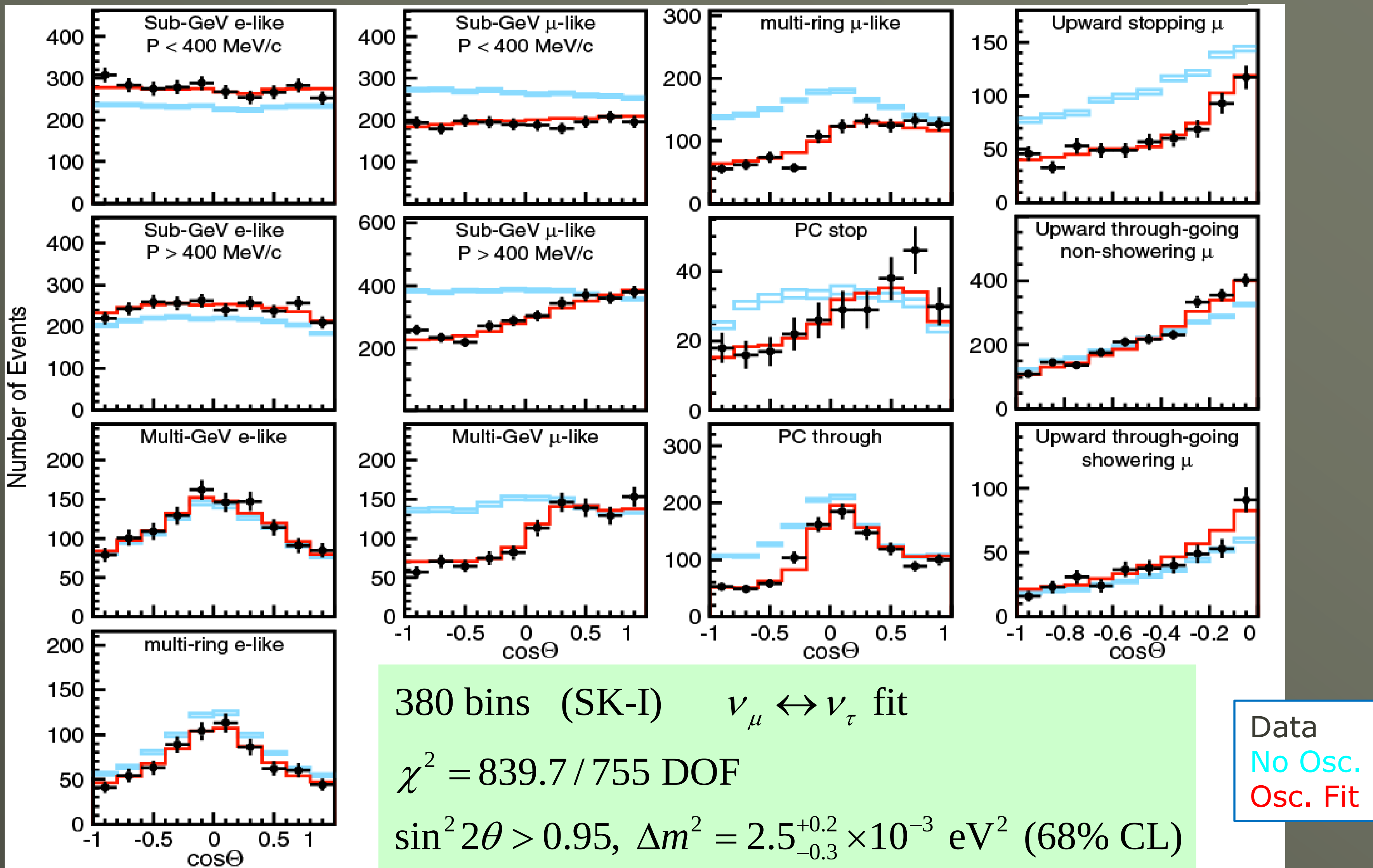
number of sys. effects (some norms. are free)

$$\chi^2 = \sum_{i=1}^{380} \frac{\left(N_i^{obs} - N_i^{\exp}(1+\sum_{j=1}^{70} f_j^i \cdot \varepsilon_j)\right)^2}{\sigma_i^2} + \sum_{j=1}^{65}\left(\frac{\varepsilon_j}{\sigma_j}\right)^2$$

$$N_i^{\exp} = N_i^0 \cdot P(\nu_\alpha \to \nu_\beta)\cdot(1+\sum_{j=1}^{39} f_j^i \cdot \varepsilon_j)$$

fractional change in predicted event rate due to variation in systematic parameter ε

Zenith Angle Spectra



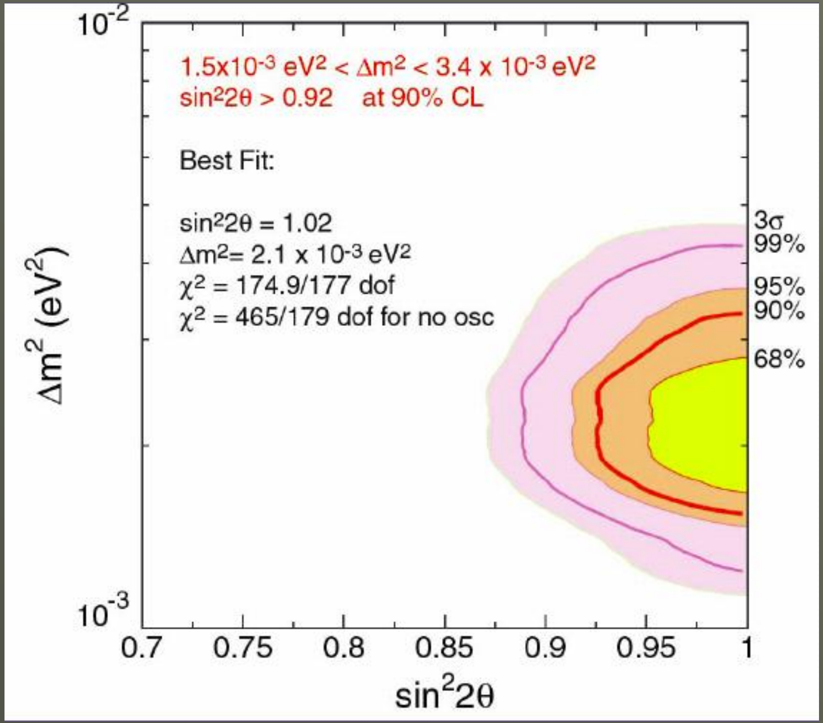
380 bins (SK-I) $\nu_\mu \leftrightarrow \nu_\tau$ fit

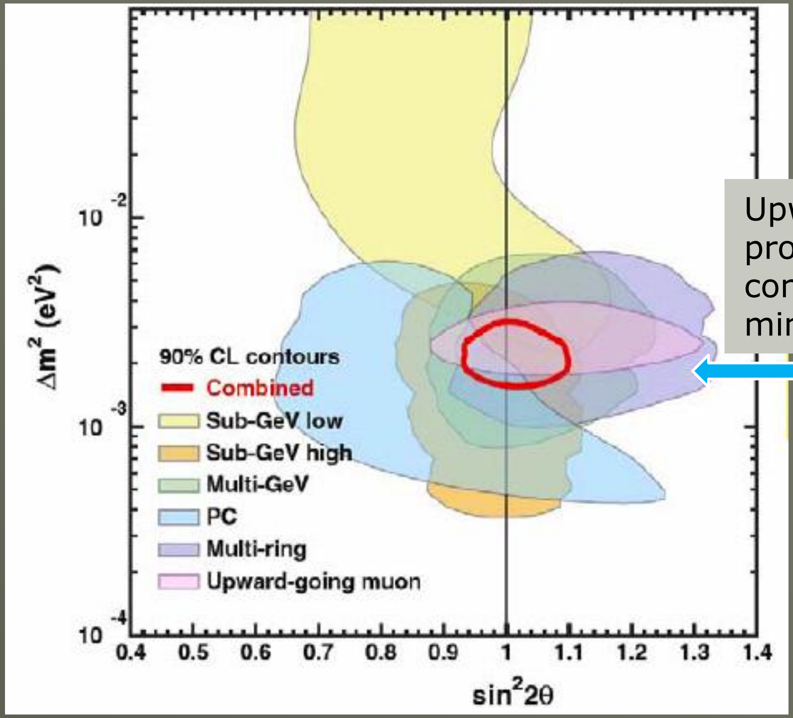
$\chi^2 = 839.7/755$ DOF

$\sin^2 2\theta > 0.95,\ \Delta m^2 = 2.5^{+0.2}_{-0.3} \times 10^{-3}$ eV^2 (68% CL)

The multiple event types and the statistics for fine binning provide powerful constraints on the allowed range of oscillation parameters.

Contours for SK-I and SK-II





Upward muons provide strong constraint on minimum Δm^2.

$$1.5\times10^{-3} eV^2 < \Delta m^2_{23} < 3.4\times10^{-3} eV^2$$

$$\sin^2 2\theta_{23} > 0.92 \quad 90\% \text{ C.L.}$$

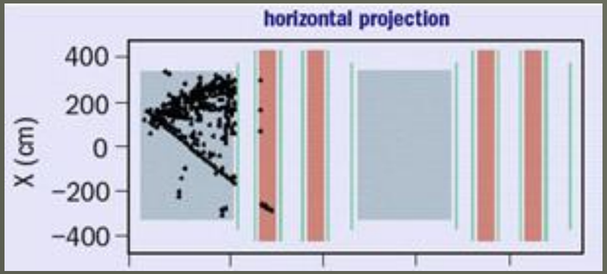
Results

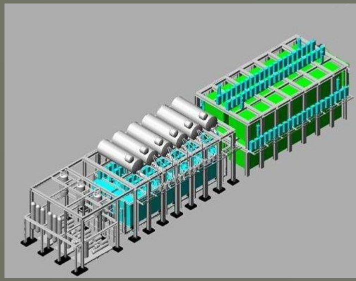
Each sub-sample looks at different ranges of energy, so individually they give different allowed regions. All are consistent with the global fit.

Has Super-K seen other effects that are expected with oscillations?

ν_τ Appearance

- goal of the CERN to Gran Sasso program
- CNGS – OPERA, ICARUS





ν_e Appearance

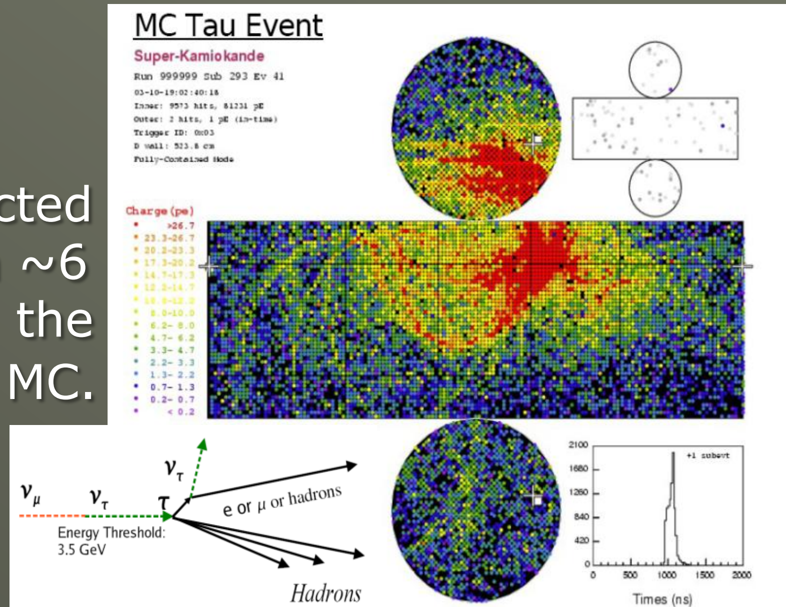
- goal of the JPARC and NuMI off-axis programs
- T2K, Tokai to Kamioka (Super-K) 250 km
- NOvA, Fermilab to Minnesota, 795 km
- Difficult for Super-K with atmospheric neutrinos

Oscillation Pattern

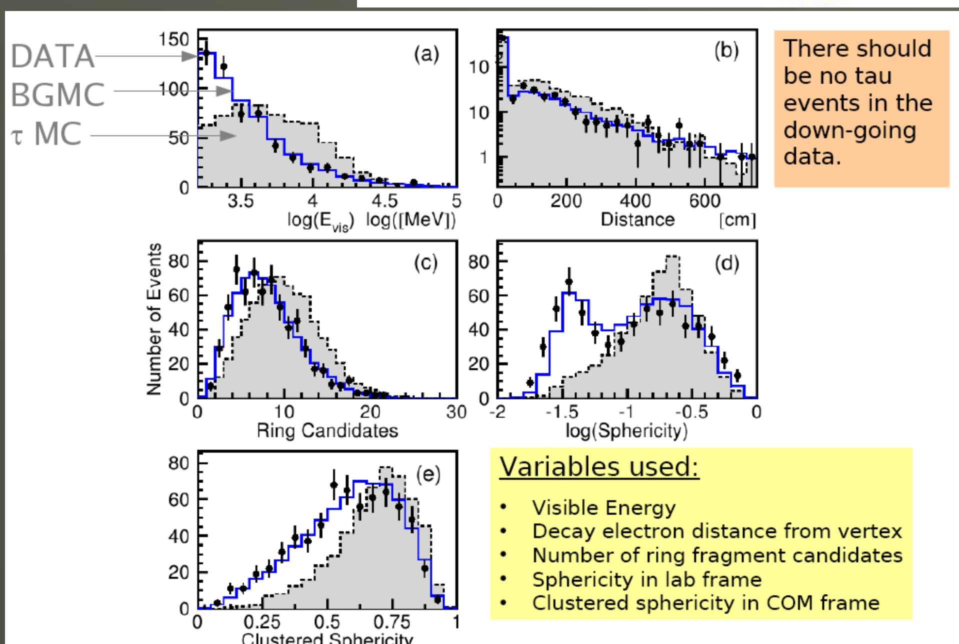
- goal of nearly all long baseline experiments
- find the characteristic dip in the L/E distribution

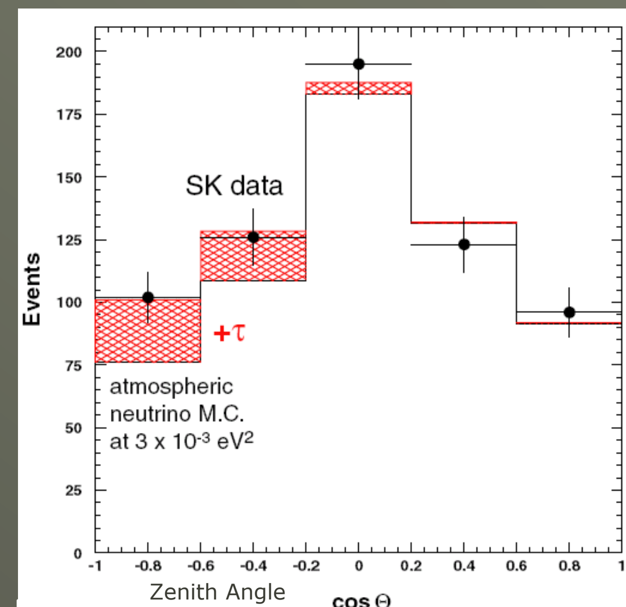
Have ν_τ interactions been seen?

Generate expected distributions in ~6 variables using the τ MC and the ν MC.



Use a neural network weighting function to assign a probability to each event as being τ-like or non-τ-like.



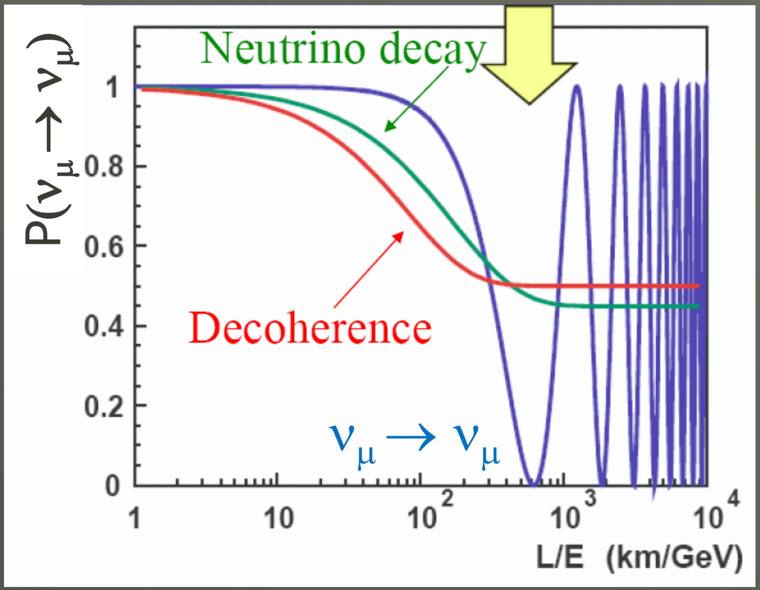


$134 \pm 48^{+16}_{-27}$ excess events
78 ± 27 excess events expected
~2.4 σ effect

Data Consistent with Tau Interactions

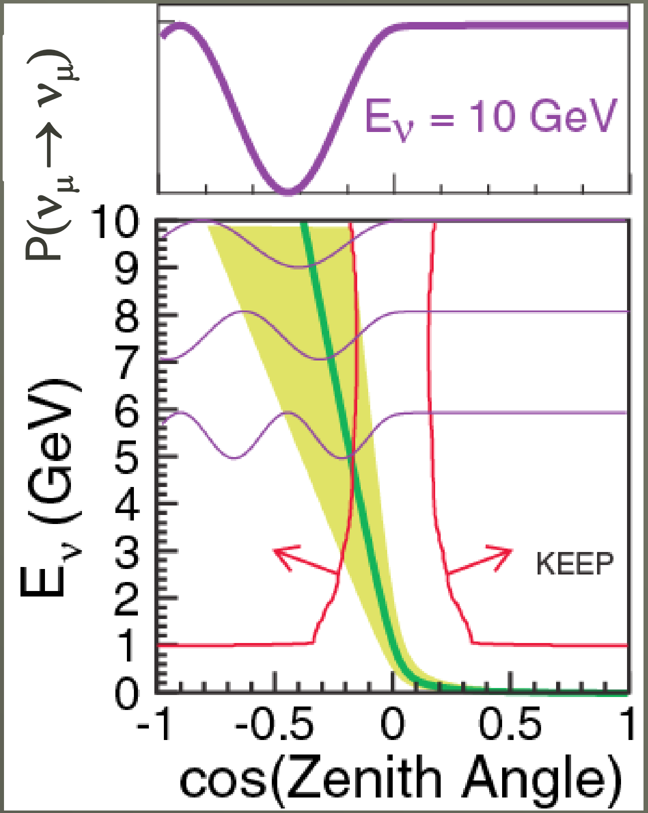
What about the oscillation pattern?

Look for oscillation minimum before averaging.



Expand Fiducial Volume (26.4 kt) to contain muons and gain statistics.

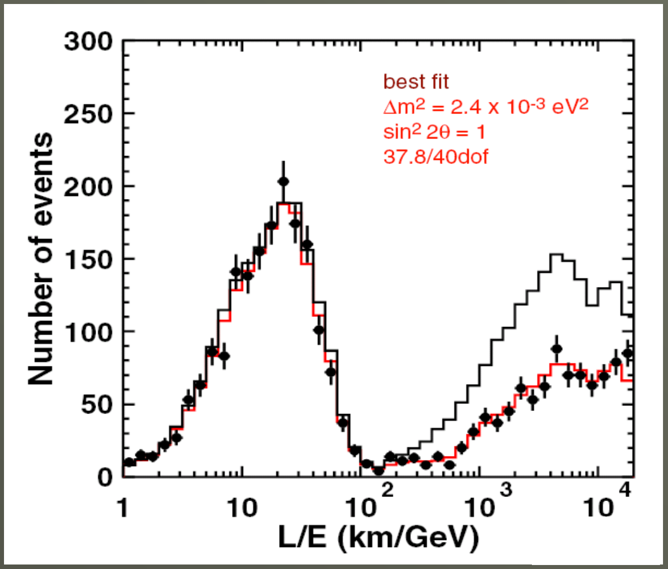
Keep events with good L/E resolution by isolating PC muons that stop in the outer detector. Use FC, Multi-ring, PC (stop, thru) events.



Eliminate:
- low energy events
- events near horizon

Green line is oscillation minimum with band to half maximum.

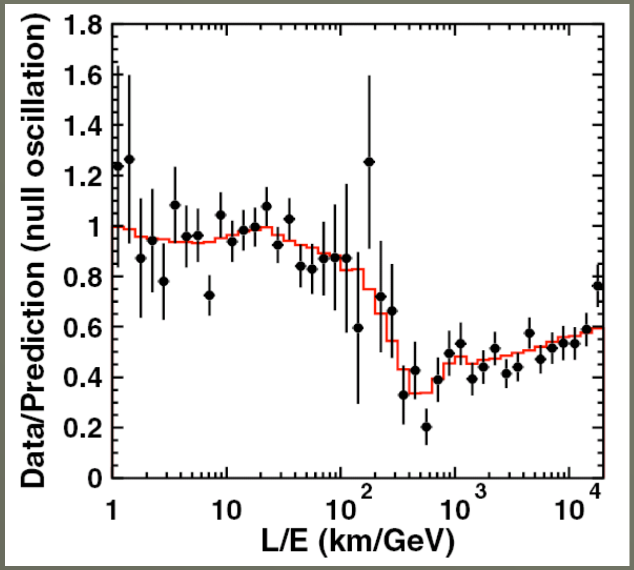
Super-Kamiokande–I L/E Results



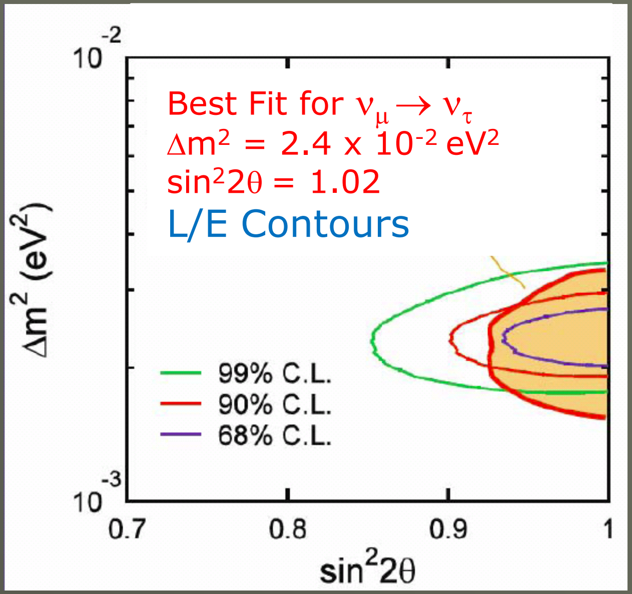
High L/E resolution μ-like data sample.

The ratio (Data/Predicted) equals one for no oscillations.

The red histogram is the best fit to $\nu_\mu \rightarrow \nu_\tau$ oscillations.



Oscillation dip seen at ~500 km/GeV



Full SK-I Data Set Shaded

Long Baseline Experiment KEK to Kamioka

A brief step back in time.

Neutrino mass measurements and study of its origin by neutrino oscillation

Submitted t

Nov.3, 1994 (a ro

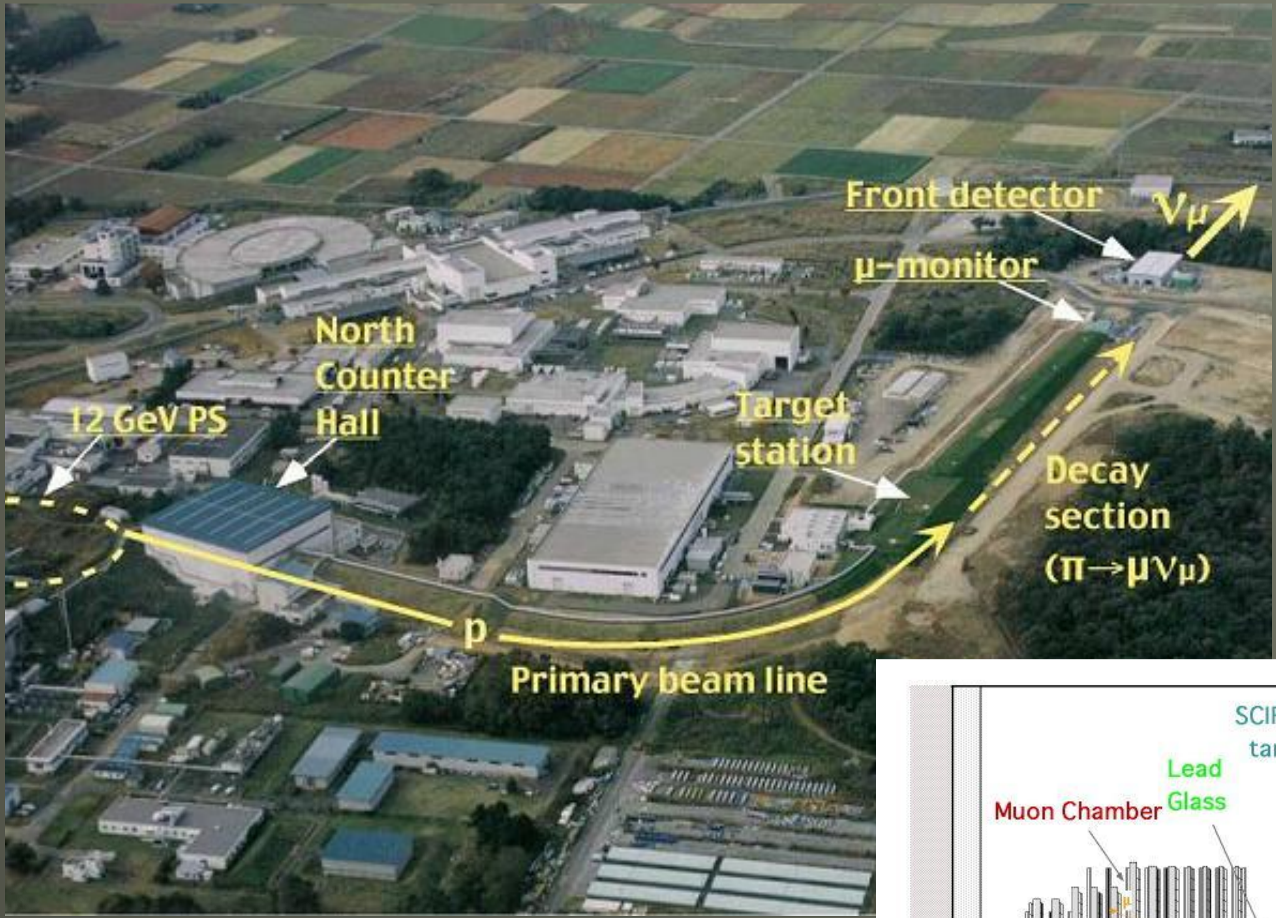
The neutrinos run thr
by the SuperK detec
a precise measureme
and its origin.

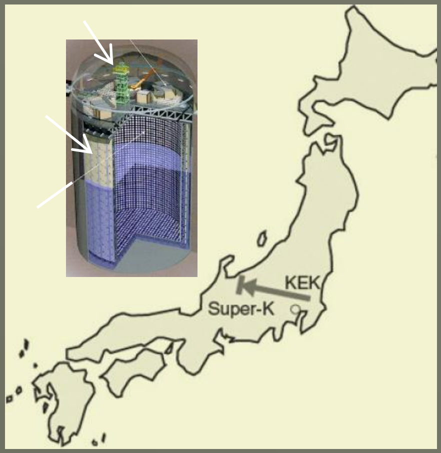
Feb.14,1995
Revised Feb.18,1995

Proposal for
a Long Baseline Neutrino Oscillation Experiment,
using KEK-PS and Super-Kamiokande

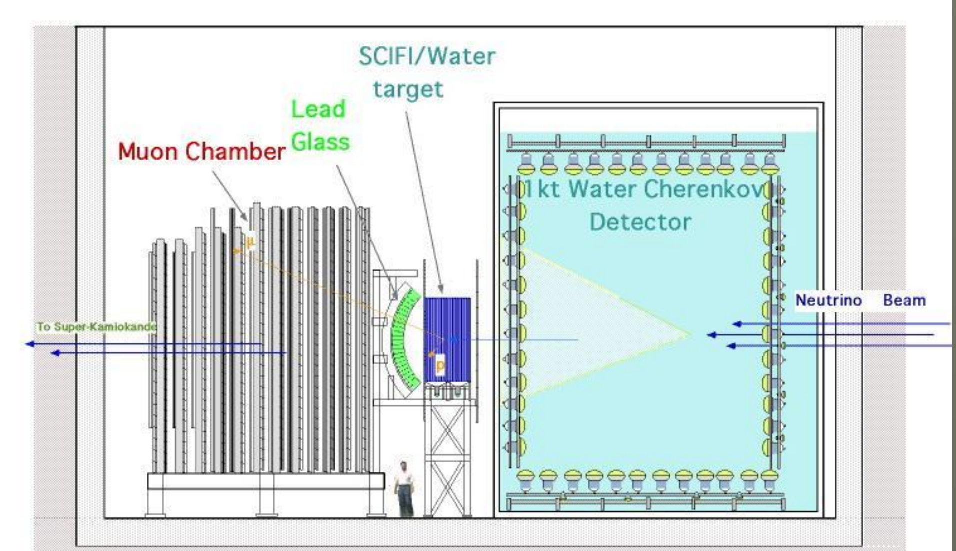
Abstract

We propose an experiment to draw a definte conclusion on the possibilities of neutrino oscillations with squared mass differences Δm^2 around 10^{-2} eV^2 which has been indicated by the Kamiokande group and by other undeground experiments (IMB, SOUDAN-II) analyzing atmospheric neutrinos. The experiment uses a well-defined muon neutrino (ν_μ) beam produced at the KEK-PS and three detectors, including the existing Super-Kamiokande detector. The experiment will be sensitive to the ν_μ->ν_e and ν_μ->ν_τ oscillations, Δm^2>3x10^{-3} eV^2 and $\sin^2 2\theta$>0.1, at more than the 3σ confidence level. The experimental methods, accelerator modification, schedule and cost estimates are described.





250 km to SK

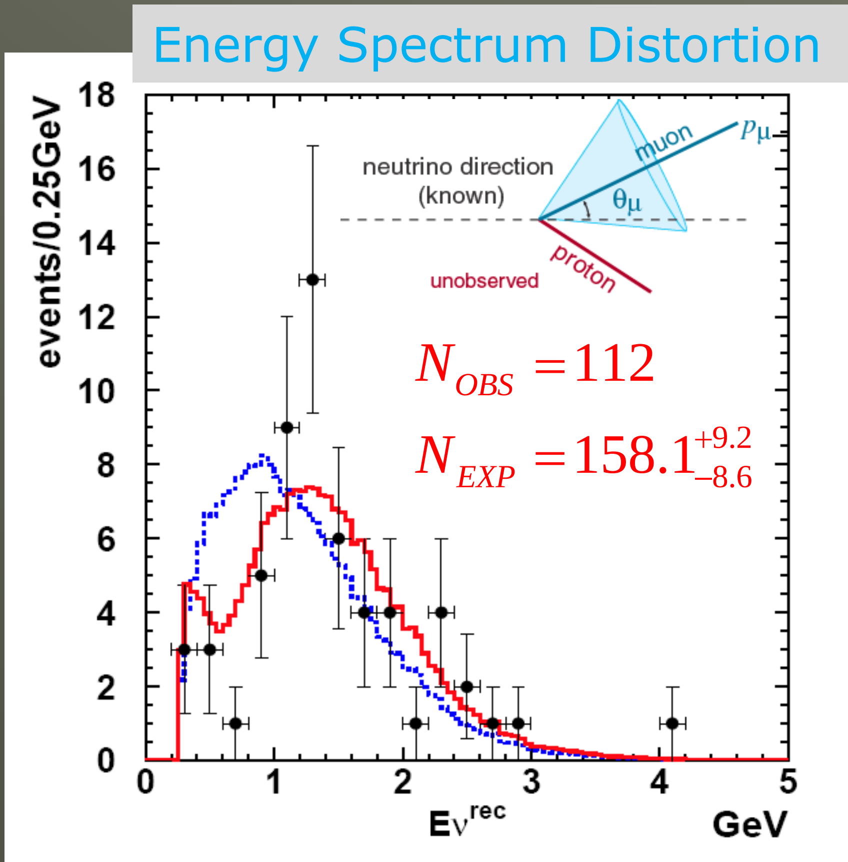


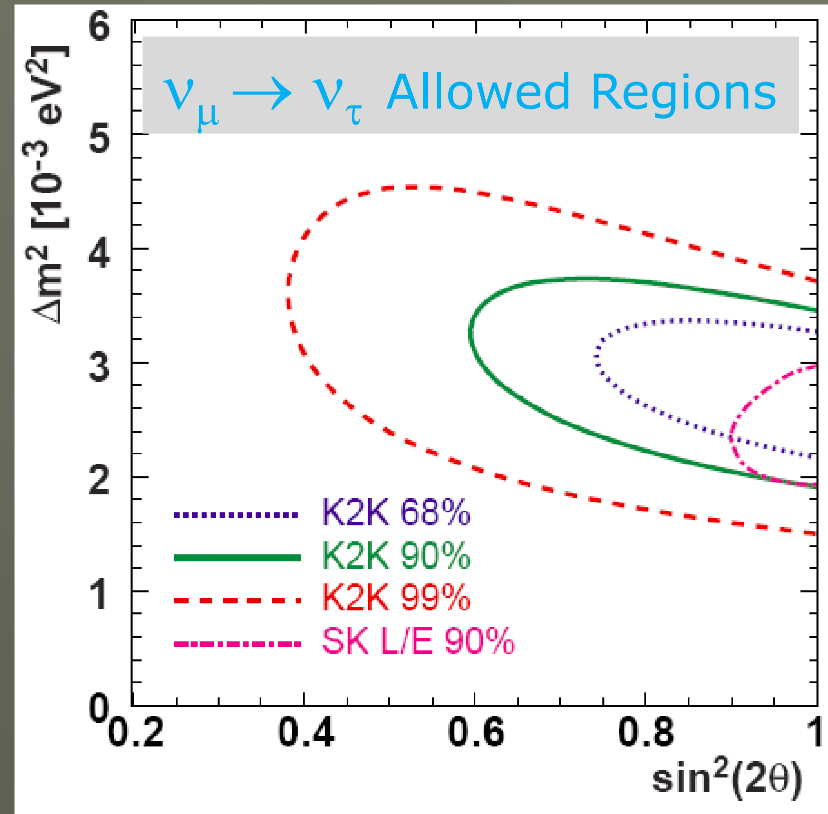
Near Detector Layout

KEK to Kamioka
K2K

$$p + \mathrm{Al} \to \pi^+ \to \mu^+ + \nu_\mu$$
$$<E_\nu> = 1.3 \text{ GeV}$$

K2K Results

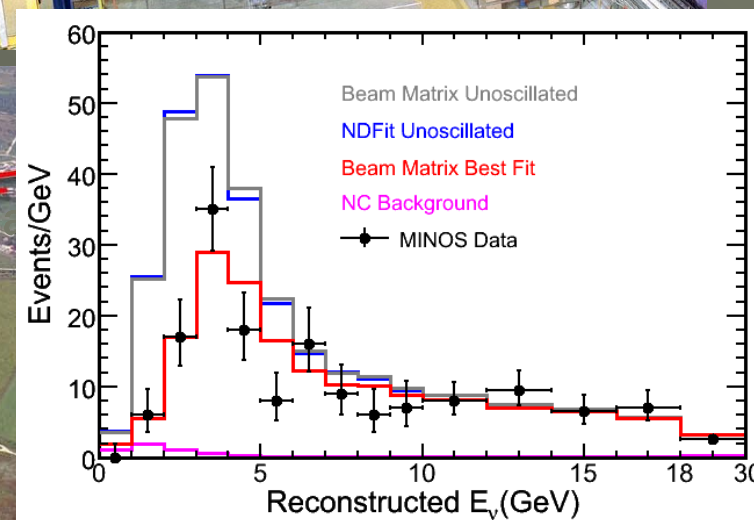




> 4σ confirmation of atmospheric neutrino mixing

MINOS Experiment

Fermilab – Soudan
$E_\nu \sim 3$ GeV
L = 735 km
Started 2005



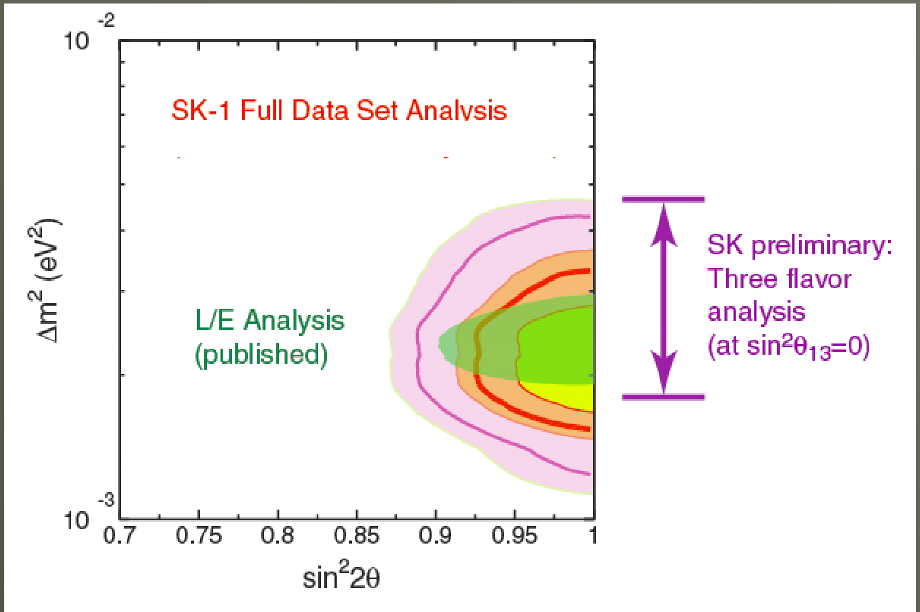
$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\ (\text{stat} + \text{syst}) \times 10^{-3}\,\text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}\ (\text{stat} + \text{syst})$$

$$\text{Normalization} = 0.98$$

$\nu_\mu \rightarrow \nu_\tau$

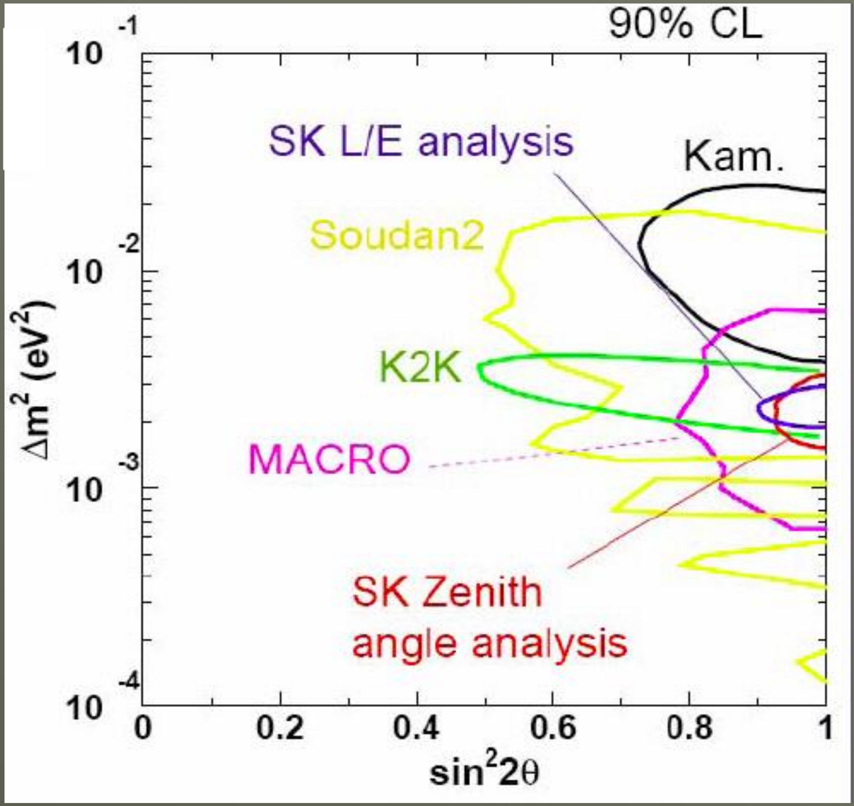
Super-K Summary



$$1.5\times10^{-3}eV^2 < \Delta m_{23}^2 < 3.4\times10^{-3}eV^2$$

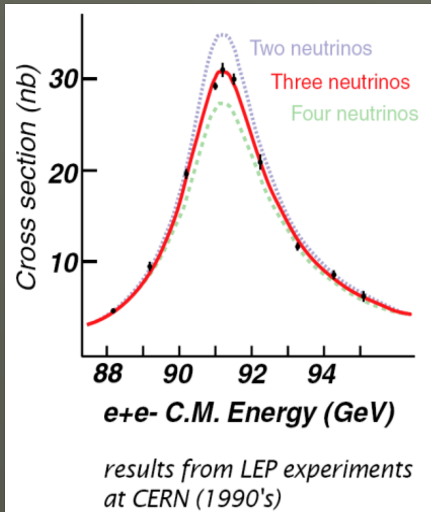
$$\sin^2 2\theta_{23} > 0.92 \quad 90\%\ \text{C.L.}$$

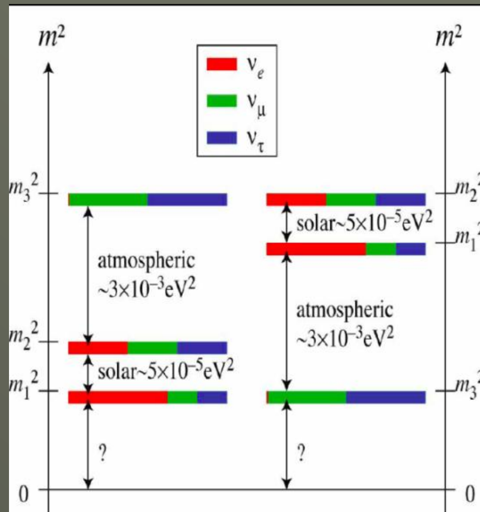
Global Summary



~~LSND~~

Number of Neutrinos is Three





The solar neutrino problem (next speaker) and the atmospheric neutrino puzzle are soundly resolved by neutrino oscillations.

But what about the other terms of the MNSP mixing matrix?

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

Maki-Nakagawa-Sakata-Pontecorvo Matrix

$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & e^{i\alpha_3/2+i\delta} \end{pmatrix}$$

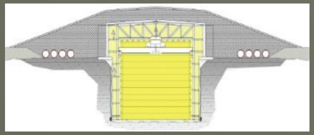
Solar | Atmospheric | CP Phase | Reactor... | Majorana Phases (Double β Decay)

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$ Three Component Flavor Mixing

- Appearance Expt?
- Mass Hierarchy?
- Value of θ_{13}?
- Violate CP?
- Majorana or Dirac?
- Absolute Mass?

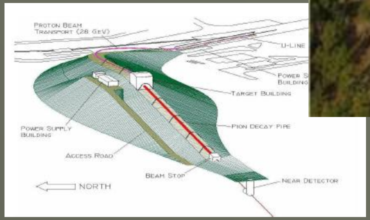
The Road Ahead

Bigger detectors, more intense beams and longer baselines



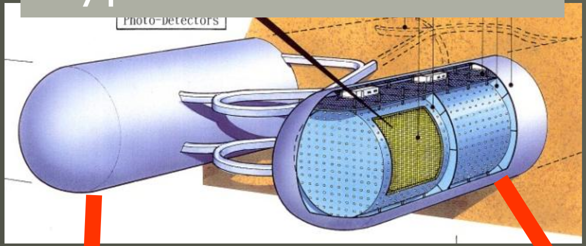
NOνA

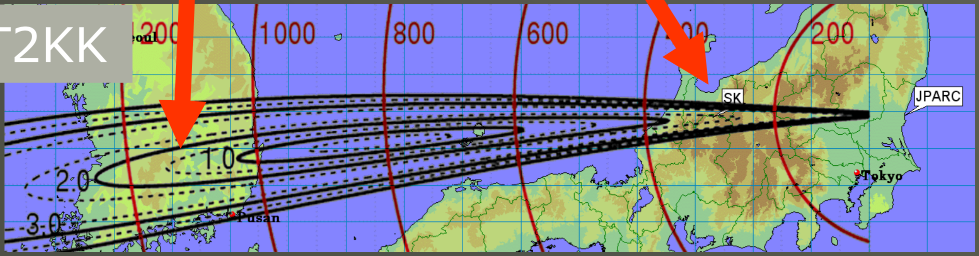
BNL



DUSEL?

Hyper-K 500 Kton

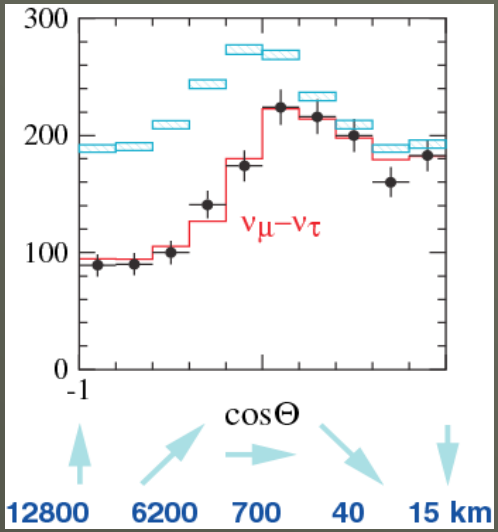




Double CHOOZ

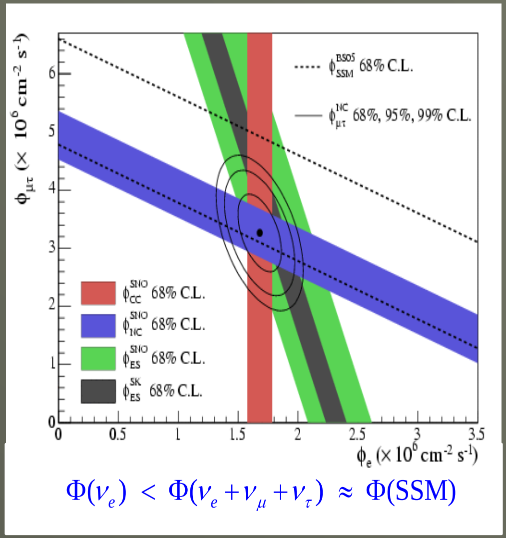
The road ahead in neutrino physics will utilize nuclear reactors and particle accelerators, but remember the first hints of neutrino mixing and the first convincing evidence of neutrino mass came from natural sources.

Atmospheric Neutrinos



Confirmed by MACRO, Soudan 2
Started by Kamiokande and IMB

Solar Neutrinos



Also important: Super-K, Kamiokande, SAGE, Gallex/GNO, Homestake