ν *Oscillation*

Review of neutrino physics - historical trajectory

Quantum mechanics of neutrino oscillation

Positive results from four current experiments

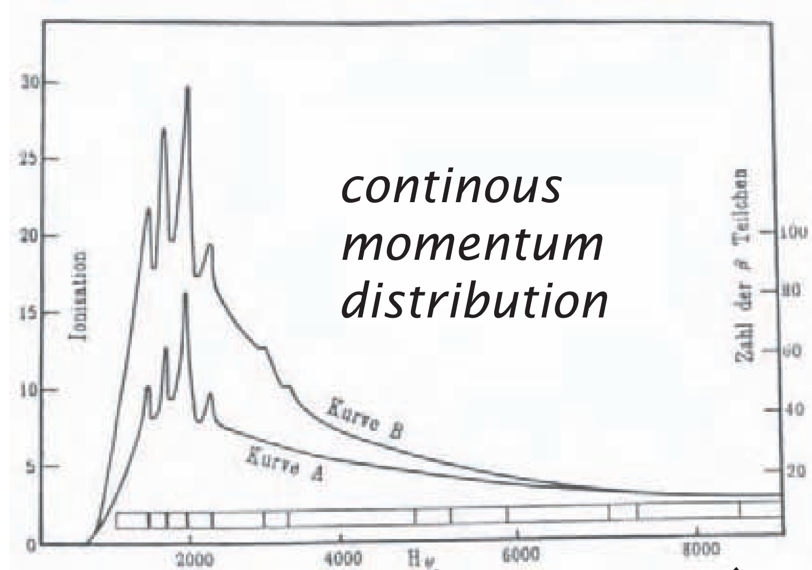
What we know and what we don't know

Your neutrino future

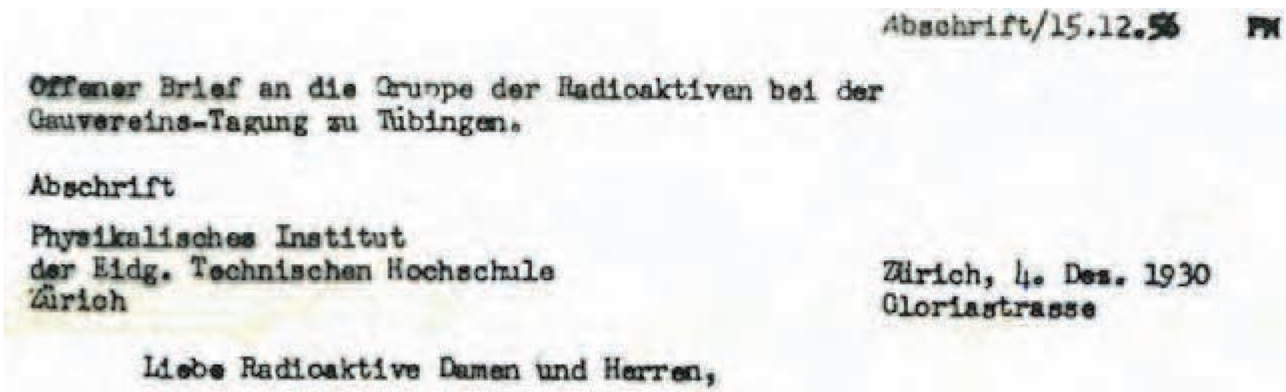
Pauli's Desperate Remedy

$n \rightarrow p + e^-$

a two-body decay:
should result in a single
fixed momentum of the electron



momentum of electron →



Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

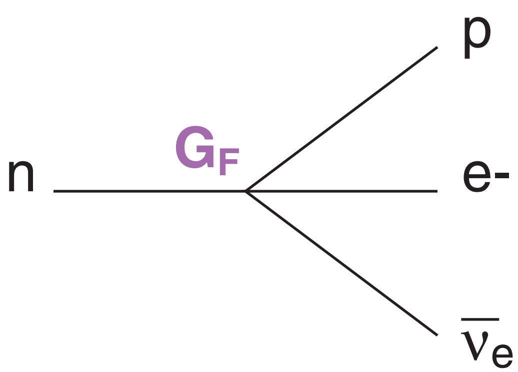
Liebe Radioaktive Damen und Herren,

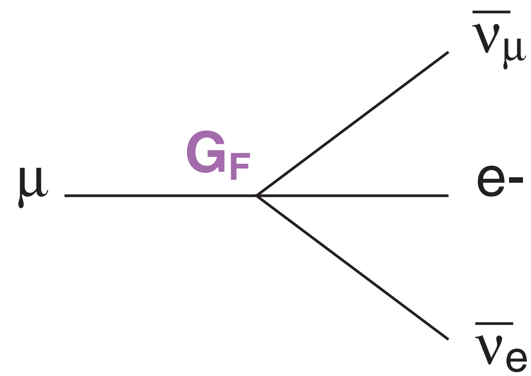
$n \rightarrow p + e^- + \nu$

Pauli's lightweight neutrino can share energy with
the electron and explain the continuous distribution.

Fermi Coupling Constant

$G_F = 1.167 \times 10^{-5}\ \text{GeV}^{-2}$



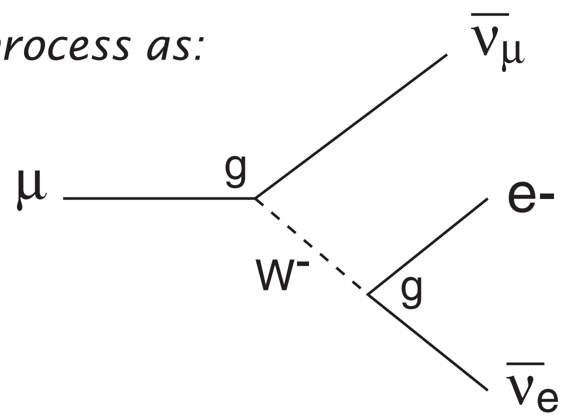


$\sigma \propto (G_F)^2[\text{energy}]^2 \quad \Rightarrow \quad \sigma \propto (G_F)^2\, M\, E_\nu \sim 10^{-38}\ \text{cm}^2$

very small!

$s = \sqrt{2ME_\nu}$

today, we understand the process as:



$$G_F = \frac{g^2}{M_W^2}$$

$$\alpha_{weak} = \frac{g^2}{4\pi}$$

$$\sim 1/29$$

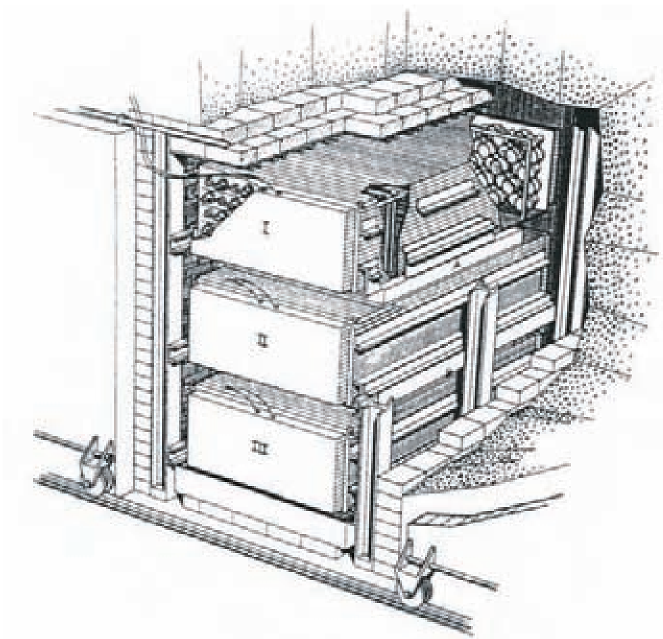
First Detection of Neutrinos

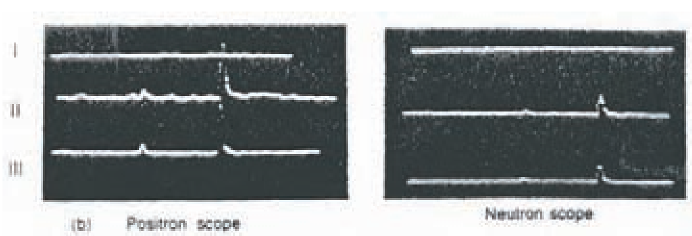
Reines & Cowen 1956
Savannah River nuclear reactor

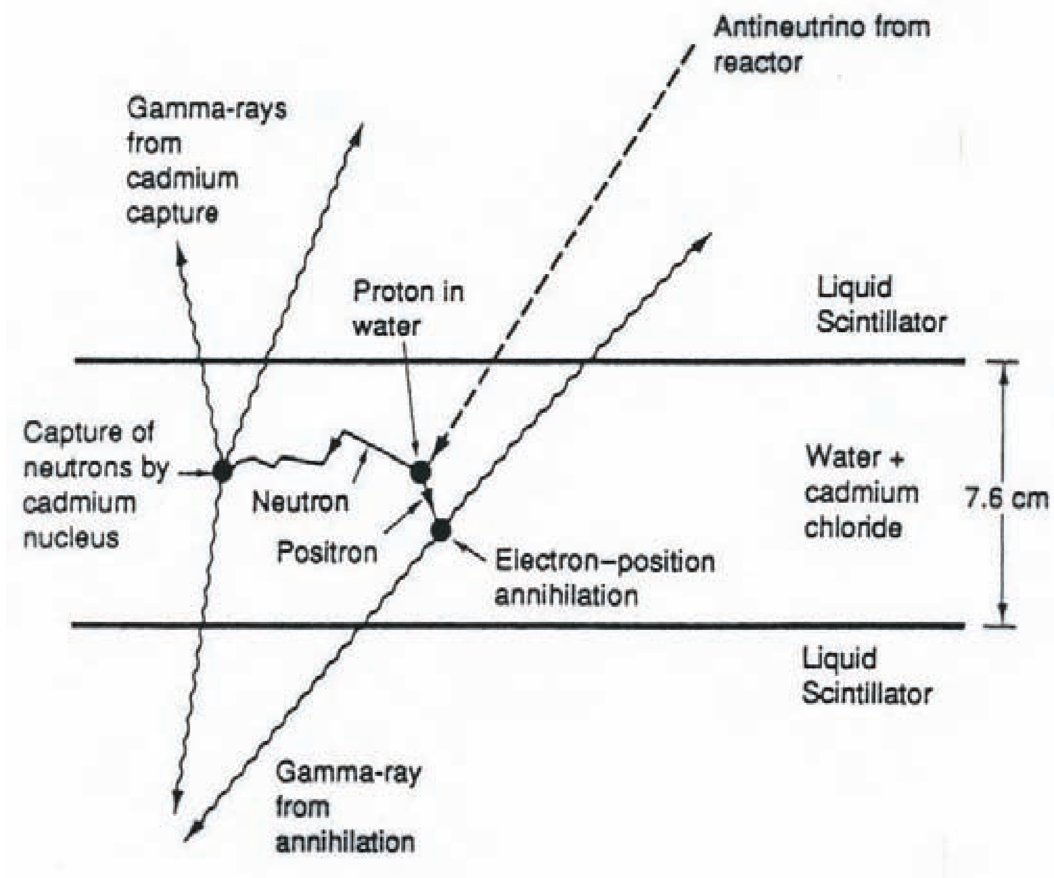
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

annihilation (e^+)

capture (n)
$\Delta t \sim 5\ \mu s$





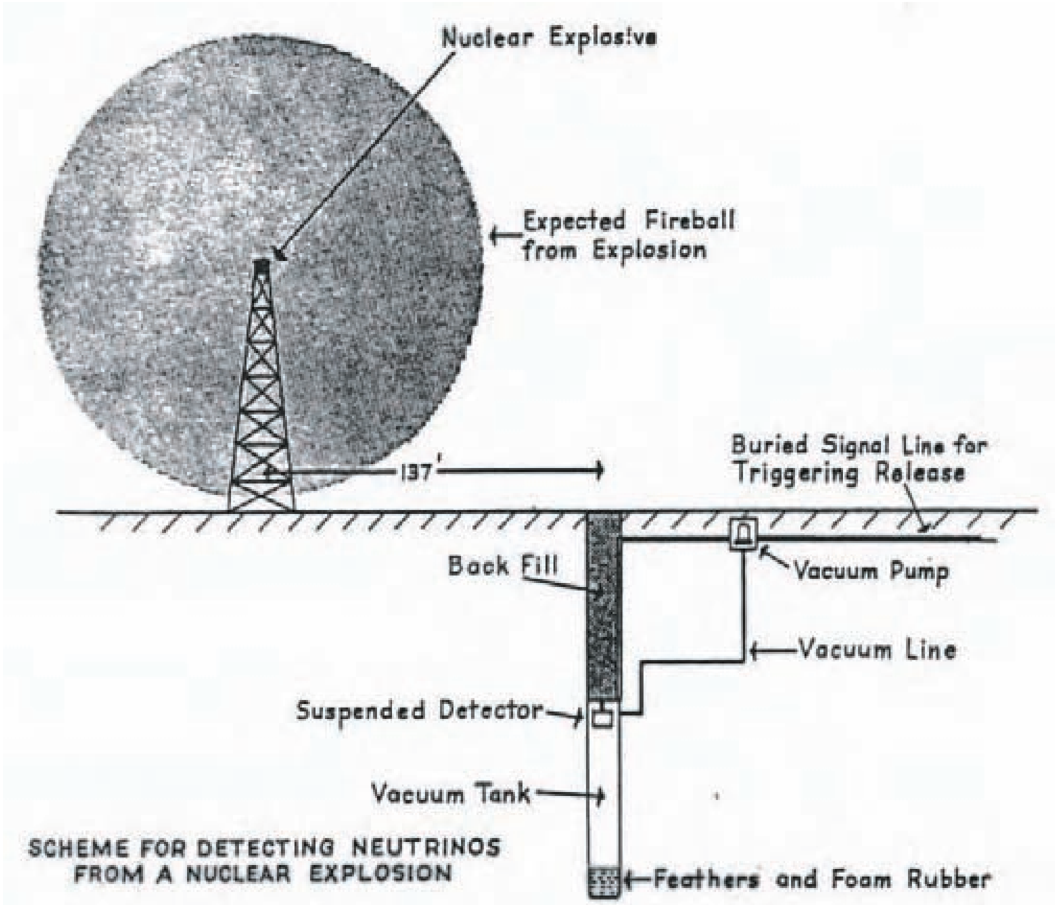


data recorded by oscilloscopes and counters

Fred Reines
1995 Nobel Prize in Physics

First Detection of Neutrinos (Proposed)

Reines & Cowen 1950



"Two Neutrino Experiment"

(mostly) muons detected in a beam of (mostly) muon neutrinos

5 GeV
protons
+
Beryllium
target

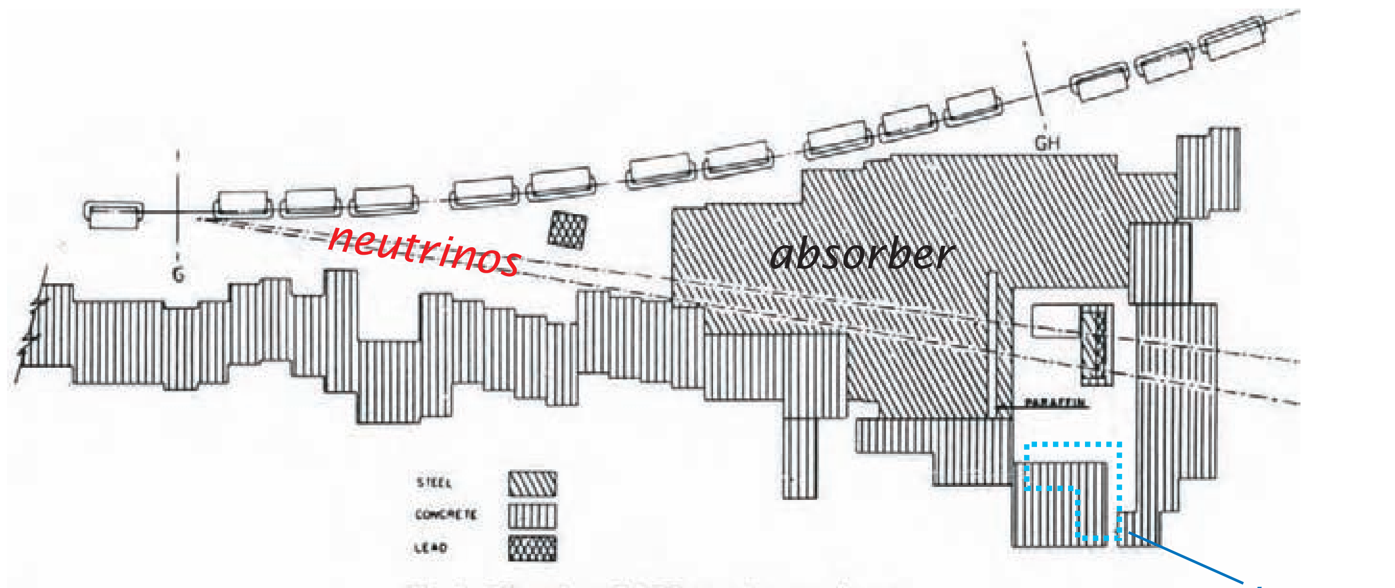


Fig. 1 Plan view of AGS neutrino experiment.

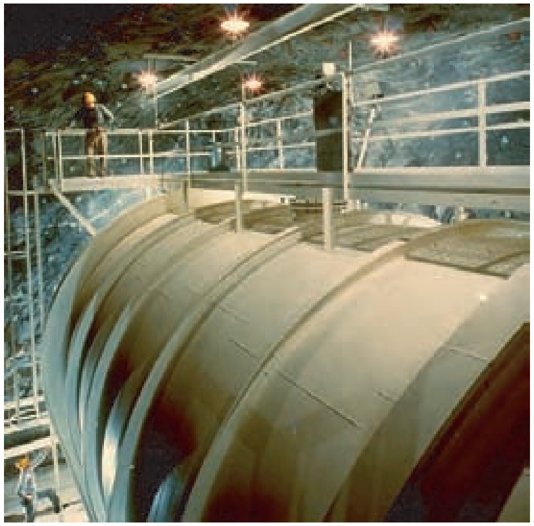
beam: *decay products of p, K*
(known to decay mostly to muons rather than electrons)

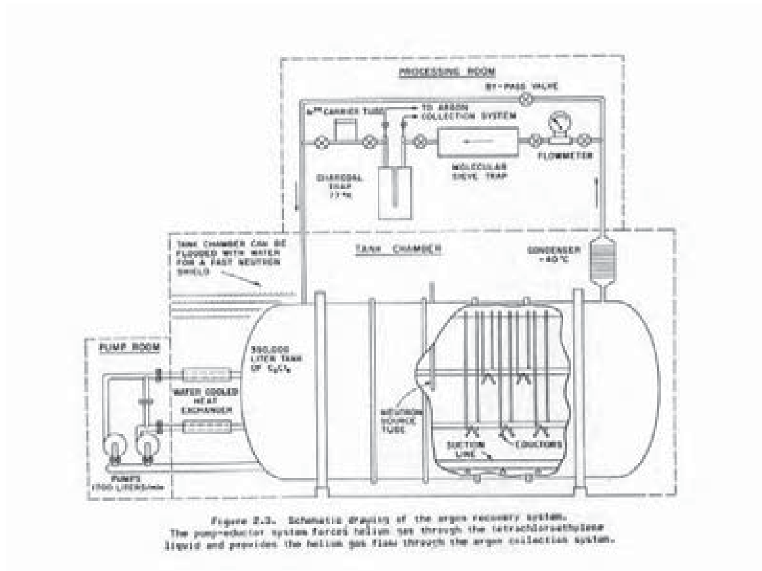
detected: *34 muons (p > 300 MeV/c)*
6 EM showers (n, ne)

Lederman, Schwartz, Steinberger
1988 Nobel Prize in Physics

Homestake Mine Solar Neutrino Experiment

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





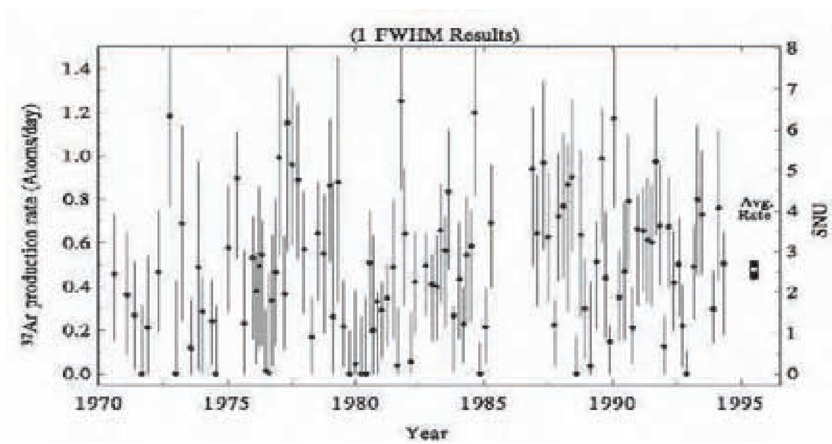
615 tons of C_2Cl_4
(dry cleaning fluid)

1500 meters depth

Individual Ar atoms extracted and counted by radioactive decay (τ ~ 35 days)

Result:

note: extraction rate less than 1 atom per day!



8.6 ± 1.2 SNU
predicted

2.56 ± 0.23 SNU
measured

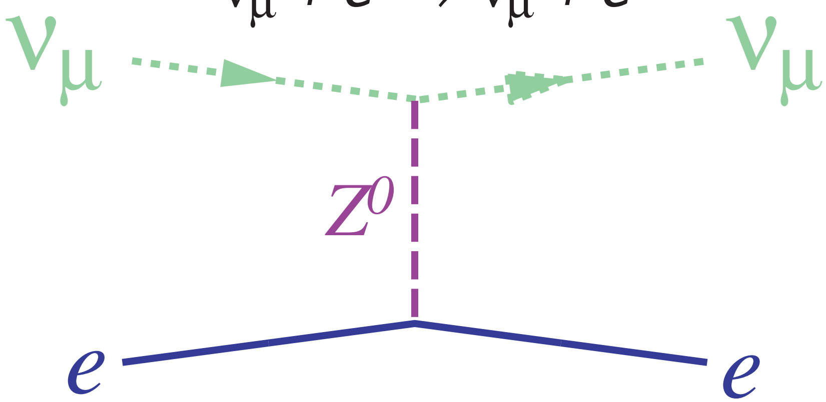
25 years ~ 800 solar neutrino events

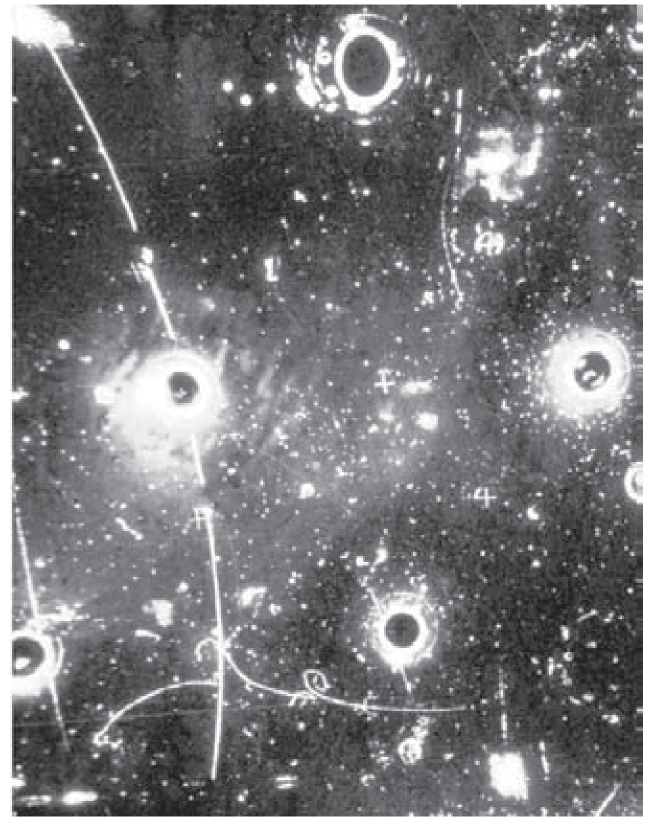
Ray Davis Jr.
2002 Nobel Prize in Physics

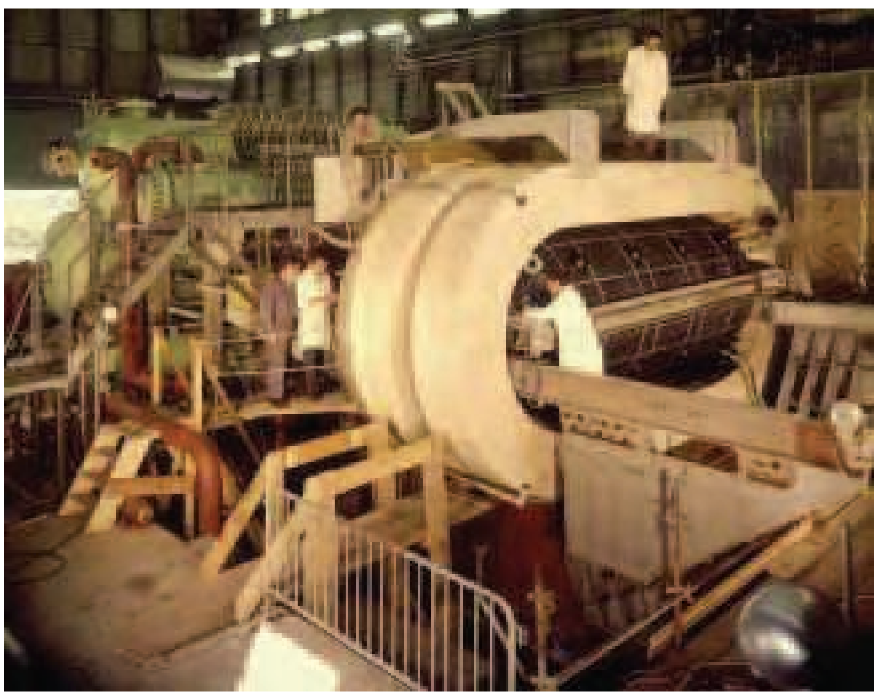
Neutral Currents and Neutrinos

discovered 1973

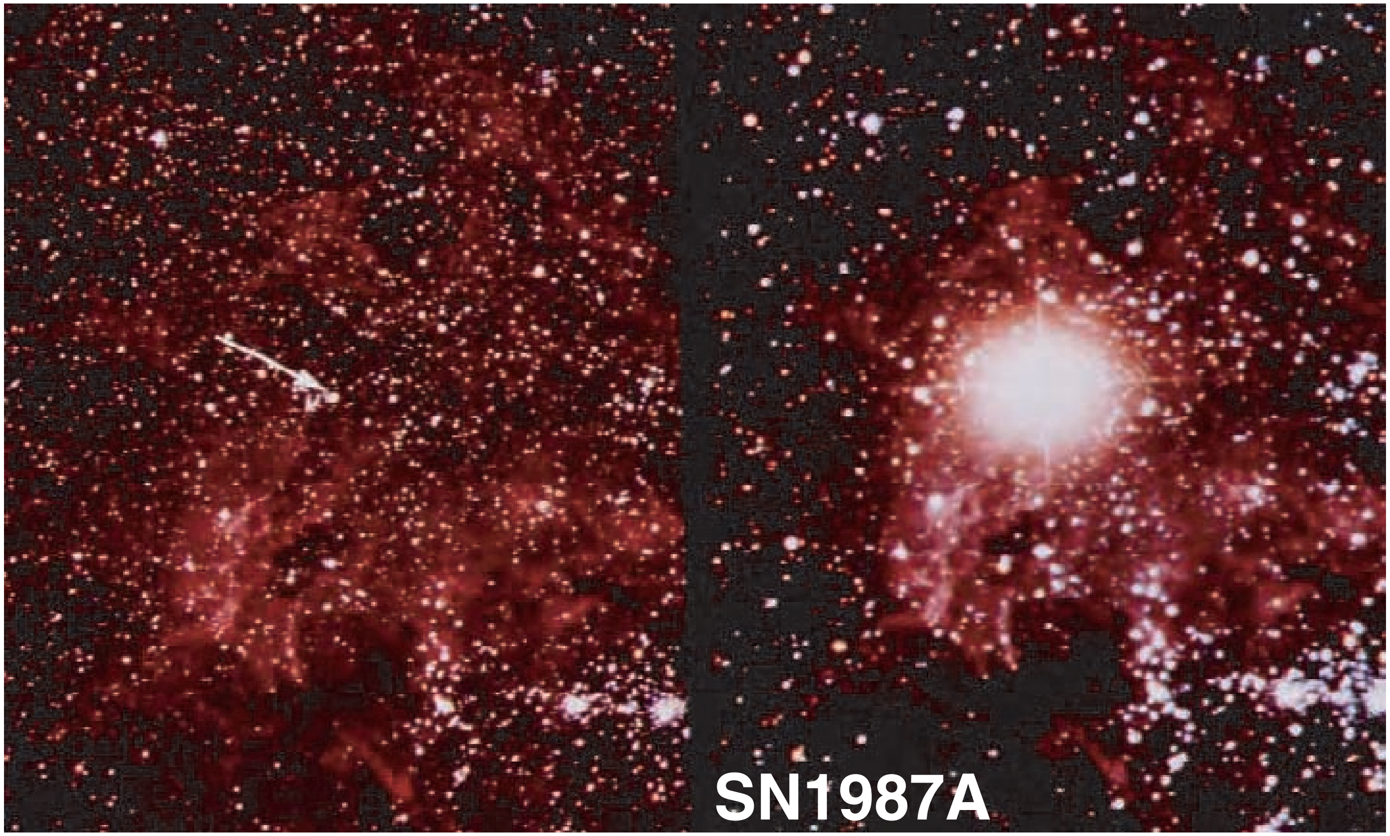
$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$





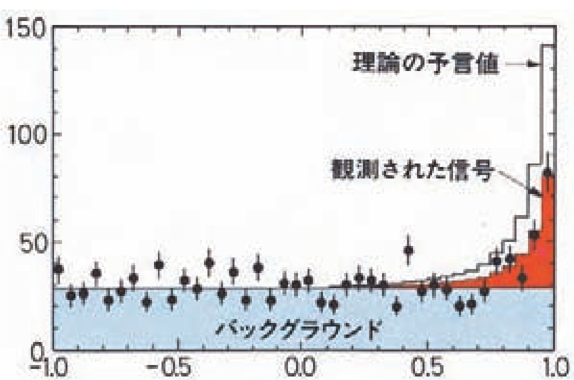


Neutrino Astronomy



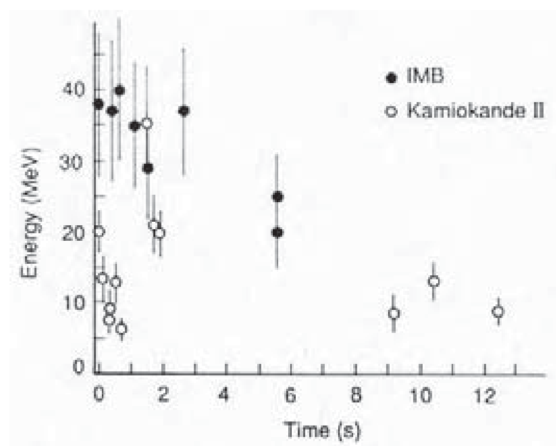
Masatoshi Koshiba
2002 Nobel Prize in Physics

Kamiokande Solar Neutrino Result

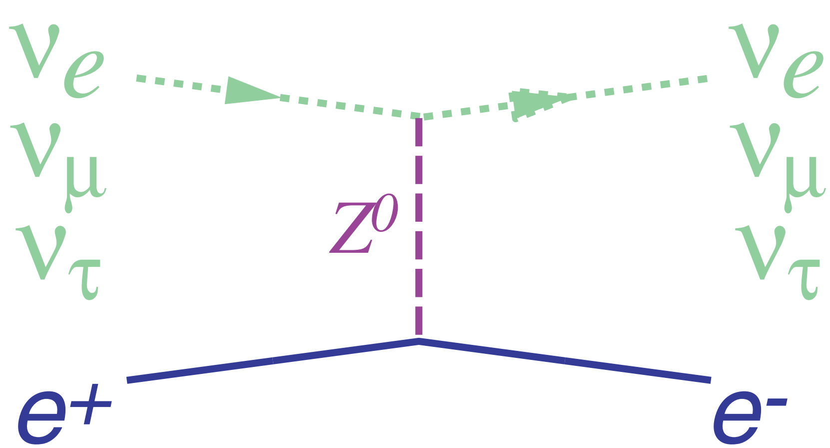


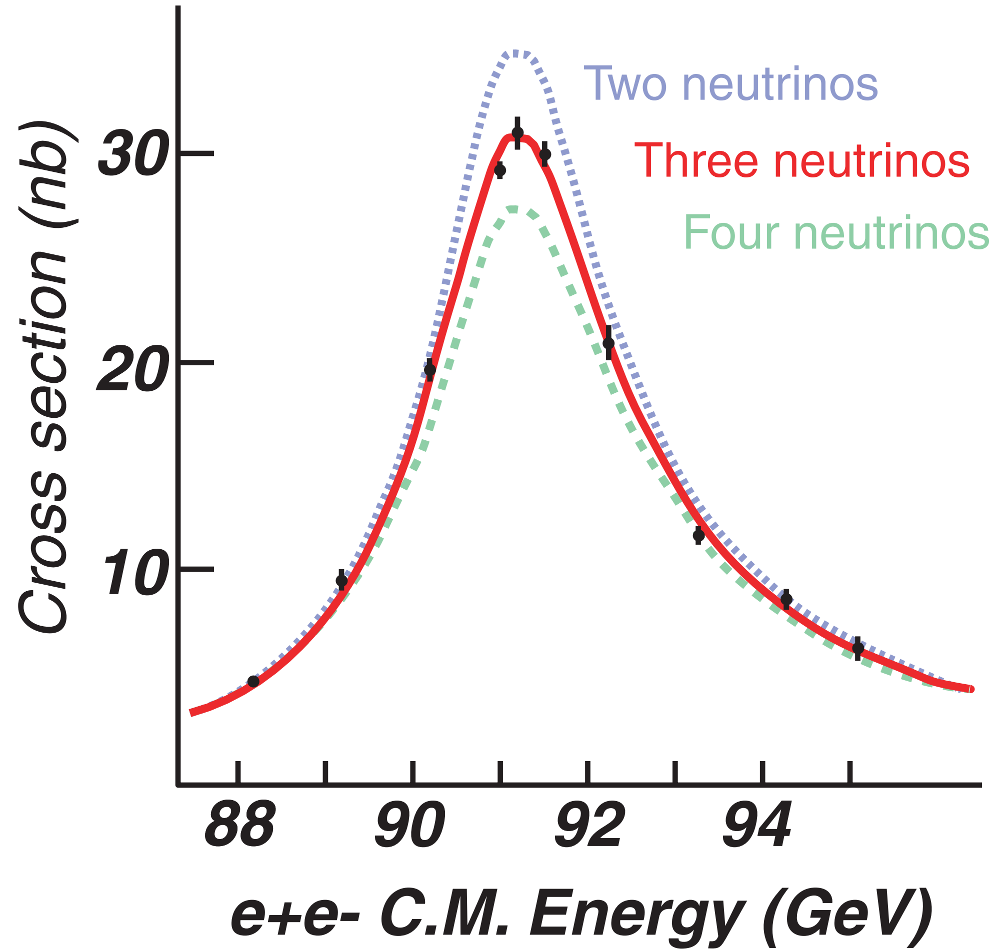
$\cos(\theta_{sun})$

Result:
46% ± 15%
of predicted flux



Three Neutrinos





results from LEP experiments at CERN (1990's)

Neutrino Oscillations

First proposed by Bruno Pontecorvo in 1957 in analogy to K^0-$\overline{K^0}$ mixing.

> Recently the question was discussed whether there exist other mixed neutral particles beside the K^0 mesons, i.e. particles that differ from the corresponding antiparticles, with the transitions between particle and antiparticle states not being strictly forbidden. It was noted that neutrino might be such a mixed particle, and consequently there exists the possibility of real neutrino-antineutrino transitions in vacuum, provided that lepton (neutrino) charge is not conserved.

- before the two-neutrino experiment, later extended to ν_e-ν_μ
- a consequence of interference of the mass states of a propagating neutrino
- requires non-zero mass and finite mixing of neutrino flavors

Neutrino Mixing

Consider the neutrino as a two-state system (we will extend to 3-states shortly),

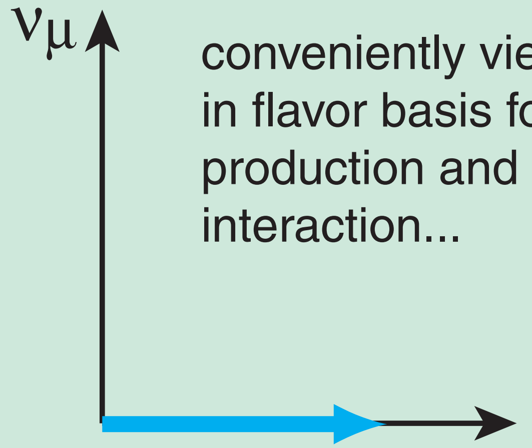
flavor

$\alpha = e, \mu, \tau$

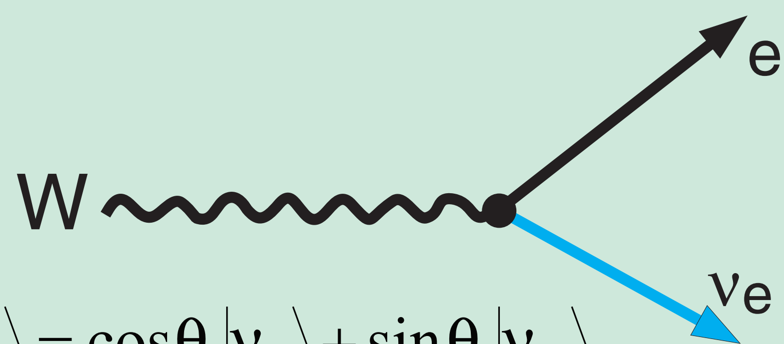
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

mass

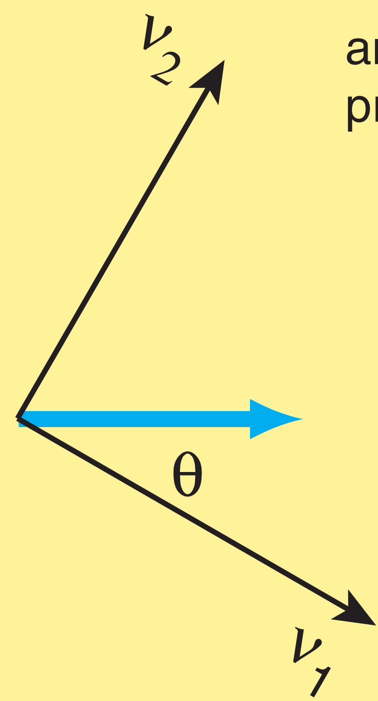
$i = 1, 2, 3$



conveniently viewed in flavor basis for production and interaction...



$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$



and in mass basis for propagation and evolution.

Schroedinger Equation:

$$i\frac{\partial}{\partial t_1}|\nu_1\rangle = m_1|\nu_1(t_1)\rangle$$

solved by:

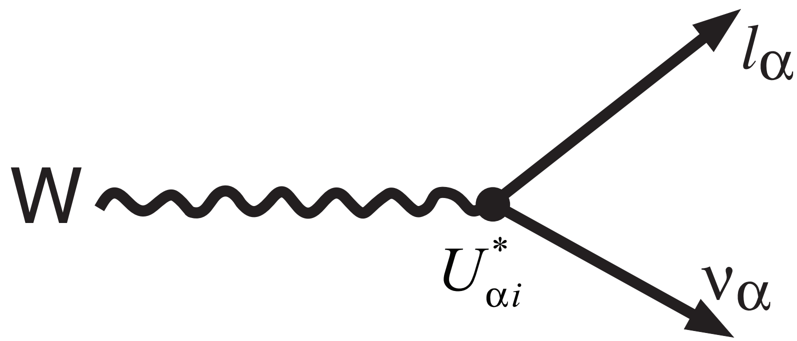
$$|\nu_1(t)\rangle = e^{-im_1 t}|\nu_1(0)\rangle$$

Mixing with Three Flavors

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

three angles plus
one complex phase

Pontecorvo-Maki-Nakagawa-Sakata Matrix (PMNS or MNS)



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

$$\left|\langle \nu_\alpha | \nu_i \rangle\right|^2 = \left|U_{\alpha i}\right|^2$$

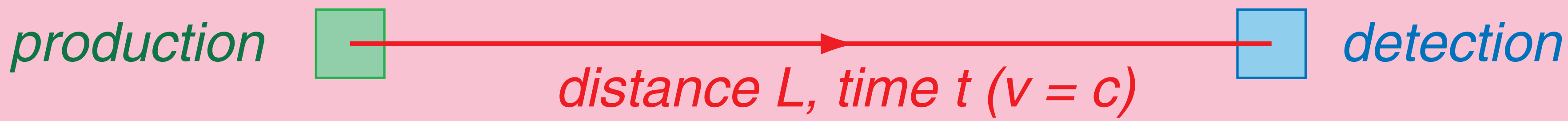
flavor fraction of α in of mass state i

Propagation in the Mass Basis

Amplitude for evolving for proper time τ:

$$\langle \nu_i(0) | \nu_i(\tau_i) \rangle = e^{i m_i \tau_i}$$

In laboratory frame variables, requiring Lorentz invariance, and v~c:



$$m_i \tau_i = E_i t - p_i L \qquad p_i = \sqrt{E^2 - m_i^2} \approx E - \frac{m_i^2}{2E}$$

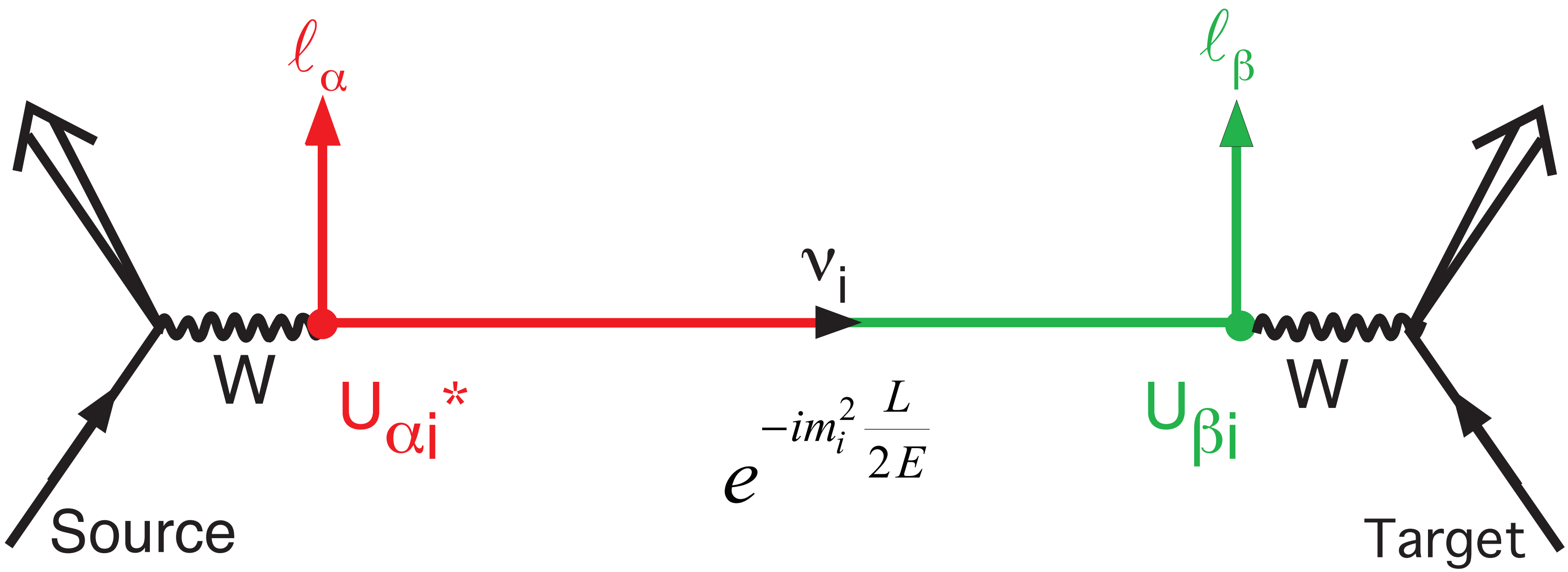
For components with common energy E that coherently interfere:

$$m_i \tau_i \approx E(t - L) + \frac{m_i^2}{2E} L$$

$$\langle \nu_i(0) | \nu_i(\tau_i) \rangle = e^{-i m_i^2 \frac{L}{2E}}$$

...ignoring common phase E(t-L)

Putting it all together...



$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin^2\left(\Delta m_{ij}^2 \frac{L}{4E}\right)$$

- sign for antineutrinos

$$\pm 2\sum_{i>j} \mathrm{Im}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin\left(\Delta m_{ij}^2 \frac{L}{4E}\right)$$

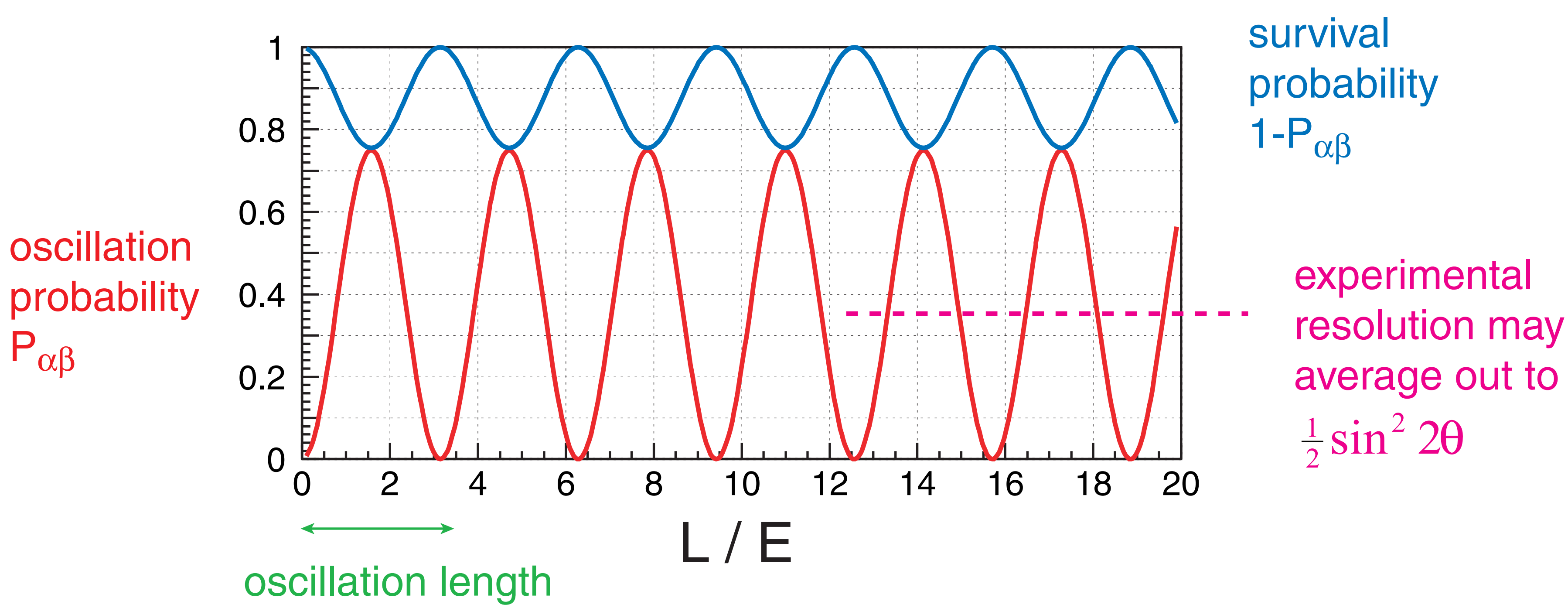
$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2 \qquad \Delta m_{ij}^2 \frac{L}{4E} = 1.27 \Delta m_{ij}^2 (\mathrm{eV}^2) \frac{L(\mathrm{km})}{E(\mathrm{GeV})}$$

with $\hbar, c \neq 1$

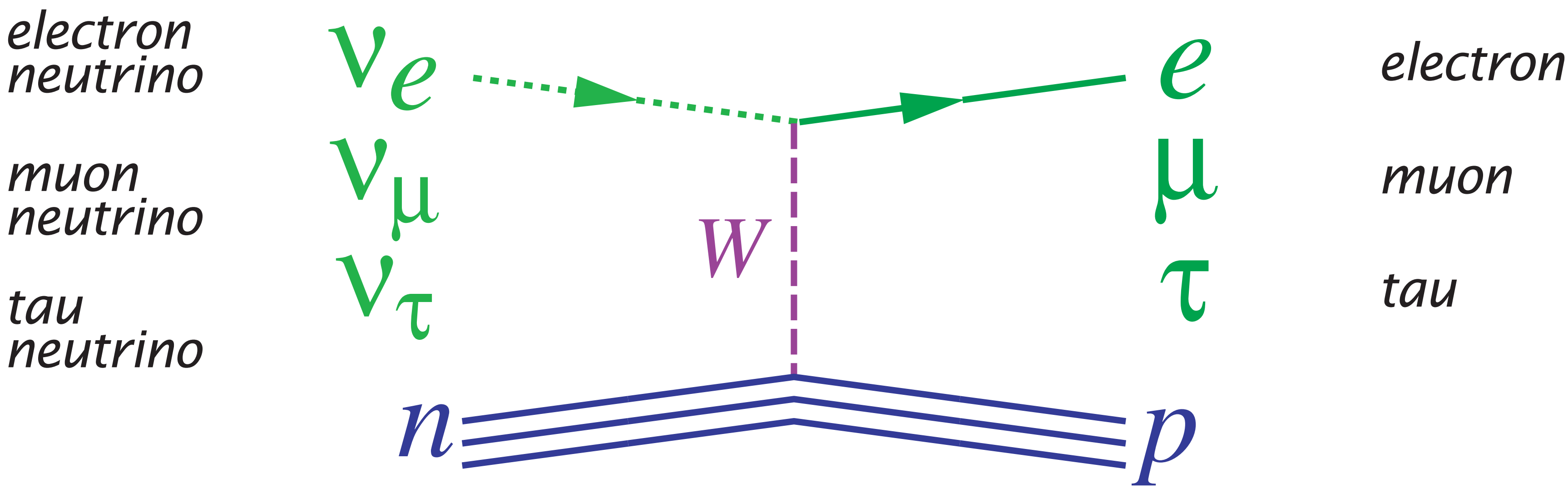
Back to Two Neutrinos

- often the case: one of the oscillatory terms remains zero under the experimental conditions (i.e. *L* too short, *E* to large etc.)

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \, \sin^2\left(1.27\Delta m_{ij}^2 \frac{L}{E}\right)$$



Appearance and Disappearance



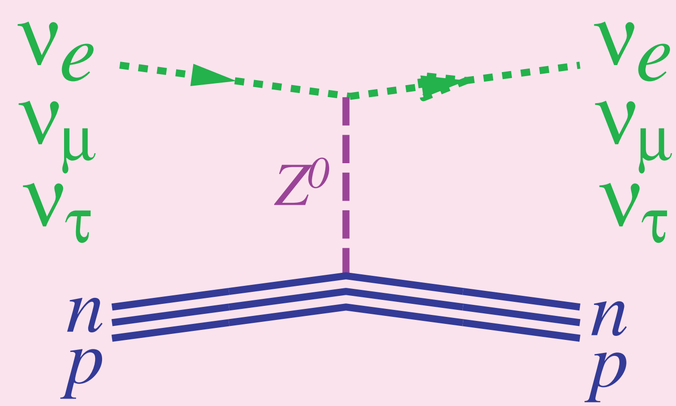
Reaction Threshold

e $\quad E_\nu > 1.5$ MeV

μ $\quad E_\nu > 110$ MeV

τ $\quad E_\nu > 3500$ MeV

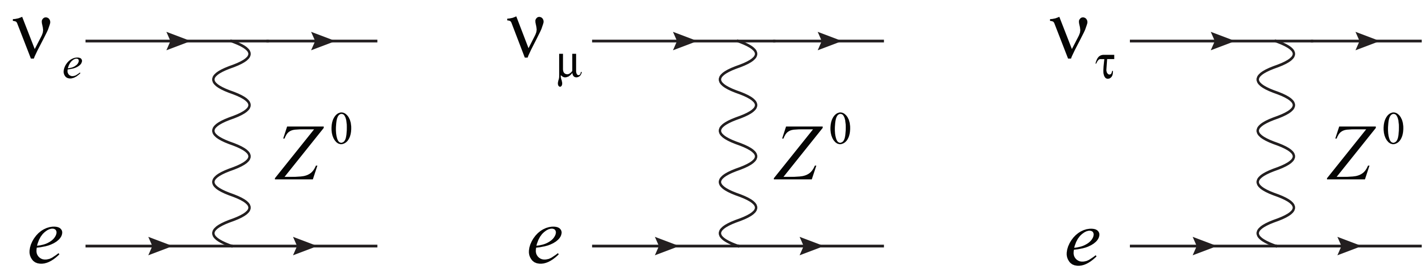
often, an experiment produces the beam neutrino below the threshold of for the production of a new flavor lepton

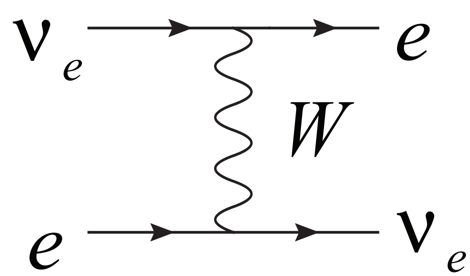


Neutral currents don't really oscillate!

Matter Effects

due to coherent forward scattering





no matter effect for $\nu_\mu \rightarrow \nu_\tau$

matter effect for $\nu_e \rightarrow \nu_\mu$

extra interaction potential $V = \sqrt{2} G_F N_e$
(- sign for anti-ν_e)

if $m_2^2 - m_1^2 < 0$ then V also changes sign

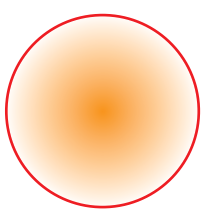
Matter Effects (continued)

$$\Delta m_M^2 = \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2}$$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2}$$

$$x = \frac{V/2}{\Delta m^2 / 4E} = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2} \sim \frac{E}{12 GeV} \text{(in earth's mantle)}$$

Mikheyev-Smirnov-Wolfenstein (MSW effect)



neutrinos produced in
Sun’s center would encounter
critical density at some point
on the way out regardless
of how small the mixing angle

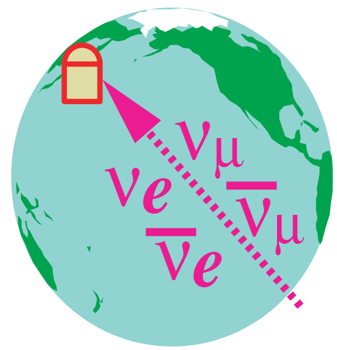
if $\sin^2 2\theta$ is small
it can become large
in matter under the
right energy and
density conditions

Neutrino Oscillation Experiments

solar neutrinos

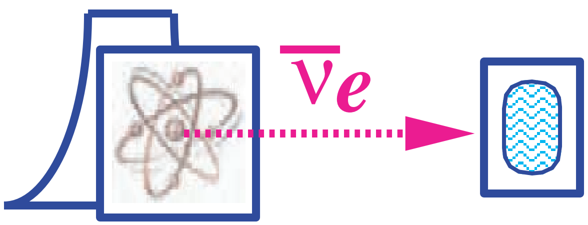
$L = 10^{11}$m
$E = 0.1$ to 15 MeV
$\Delta m^2 \sim 10^{-10}$ to 10^{-12} eV^2 (vacuum)
$\Delta m^2 \sim 10^{-4}$ to 10^{-10} eV^2 (matter effects)

atmospheric neutrinos



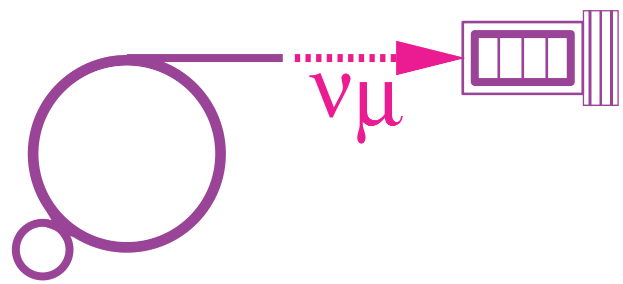
$L = 10$ to 10000 km
$E = 0.1$ to 10 GeV
$\Delta m^2 \sim 10^{-1}$ to 10^{-5} eV^2

reactor neutrinos



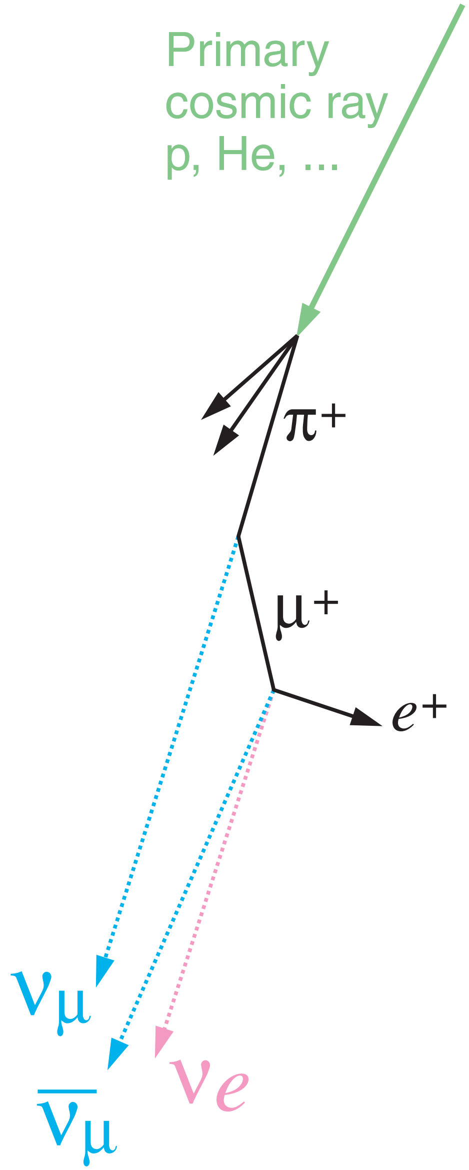
$L = 100$ to 10000 m
$E = 3$ MeV
$\Delta m^2 \sim 10^{-2}$ to 10^{-5} eV^2

accelerator neurinos

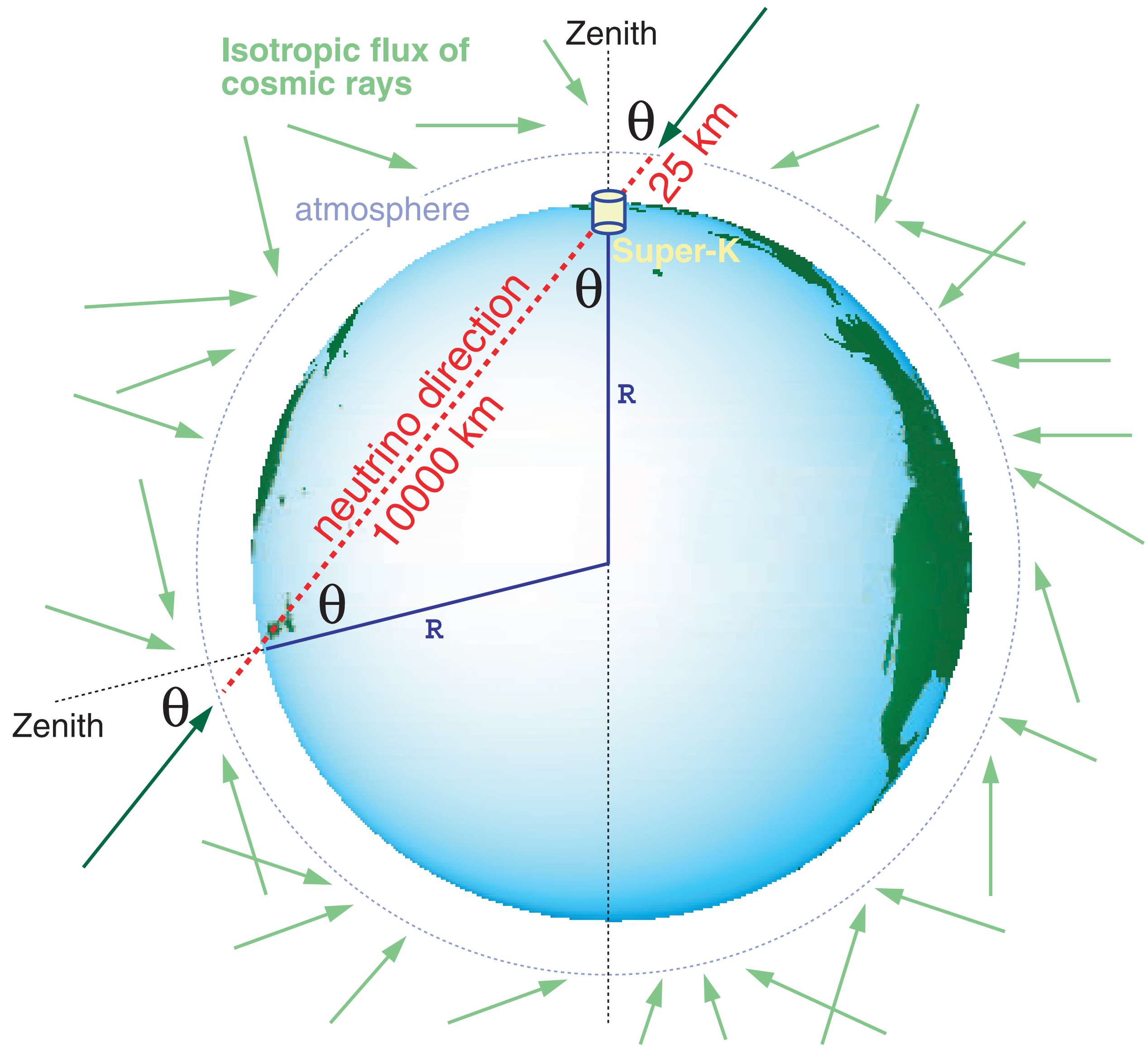


$L = 0.1$ to 1000 km
$E = 1\text{-}10$ GeV
$\Delta m^2 \sim 10^{0}$ to 10^{-4} eV^2

Atmospheric Neutrinos



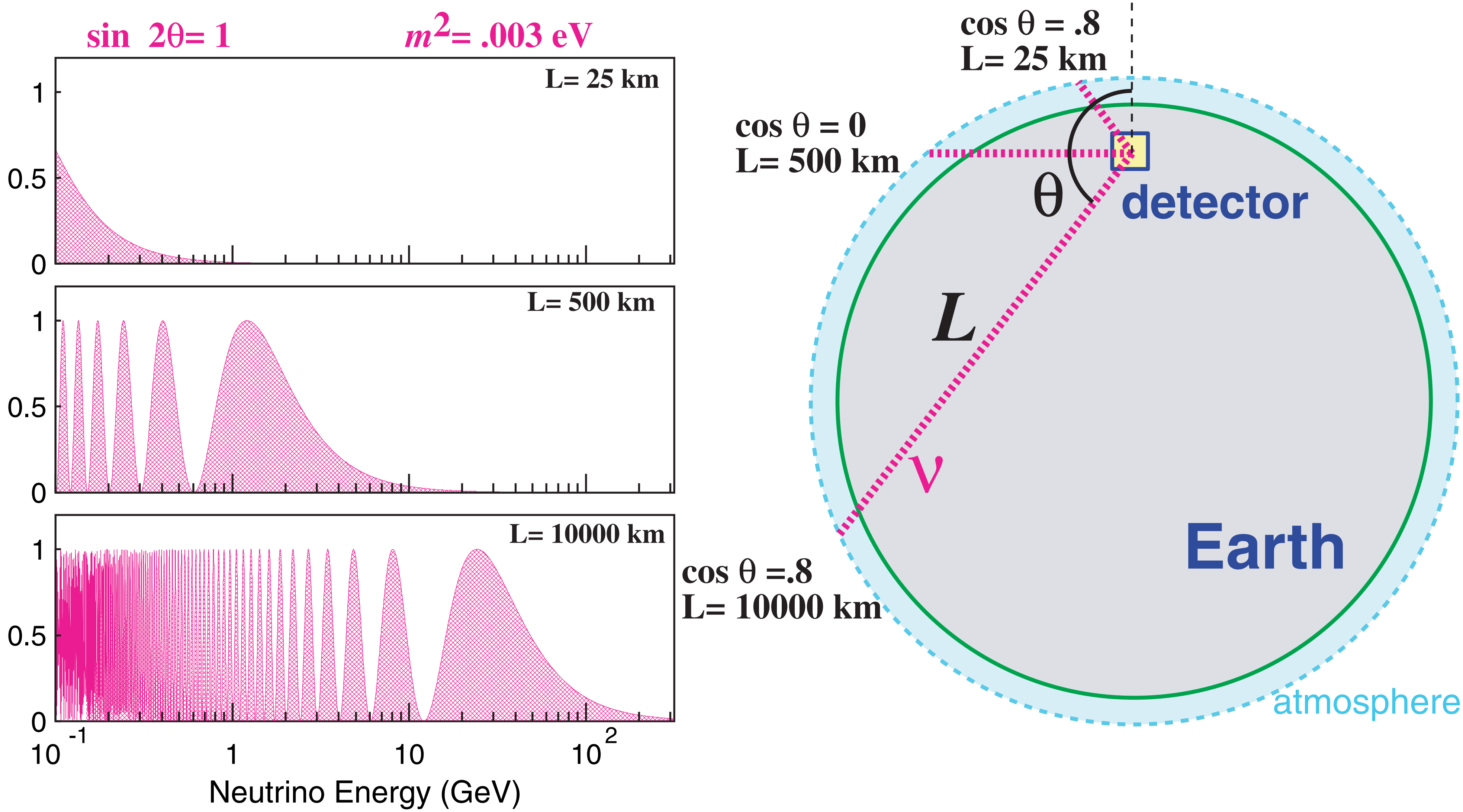
Ratio of ν_μ/ν_e ~ 2
(for E_ν < few GeV)



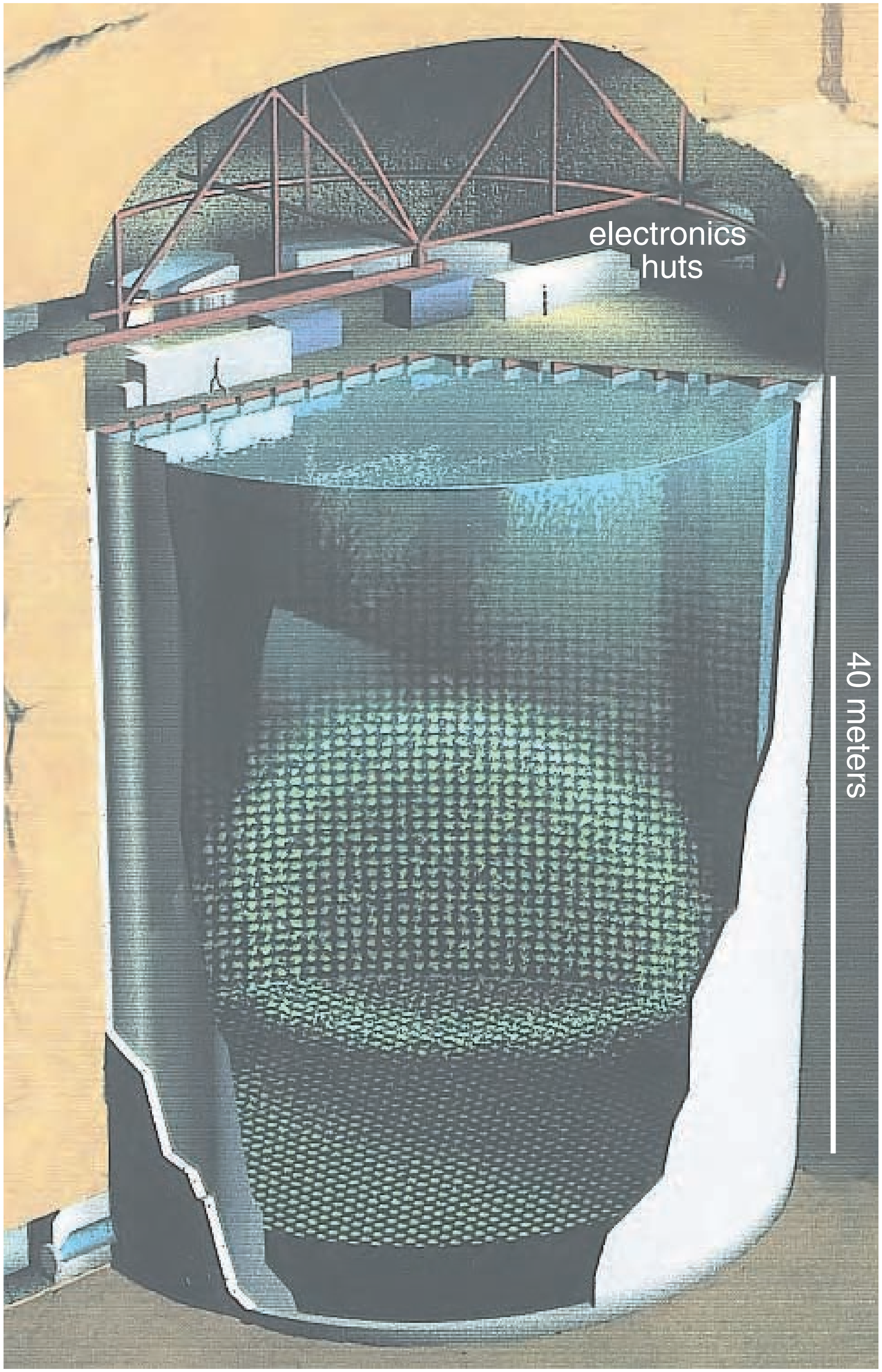
Up/Down Symmetric Flux
(for E_ν > few GeV)

Atmospheric Neutrino Oscillation

$$P_{\nu\nu'} = \sin^2 2\theta \ \sin^2 \frac{1.27\,\Delta m^2 L}{E}$$



Super-Kamiokande Experiment



Inner detector

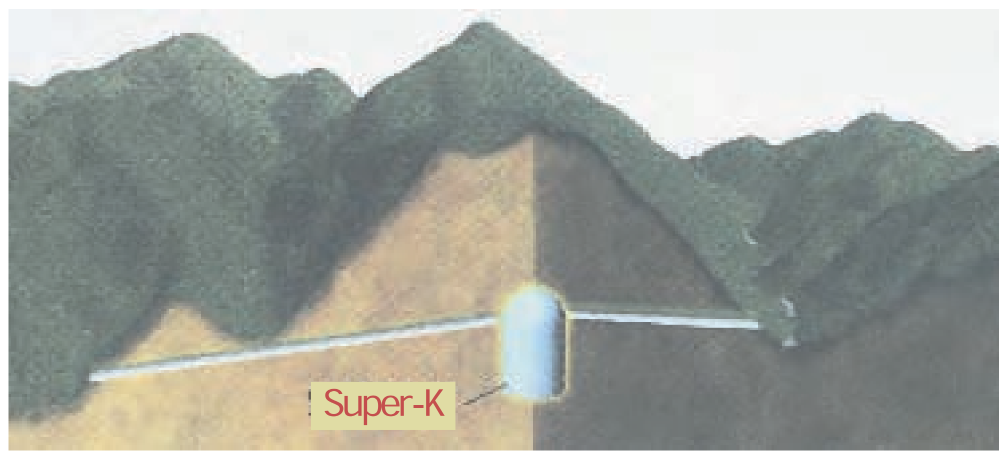
22.5 kton fiducial mass
11134 50cm photomultiplier tubes
40% photocathode coverage
~2 ns PMT timing resolution
~85 m water attenuation length

Outer detector

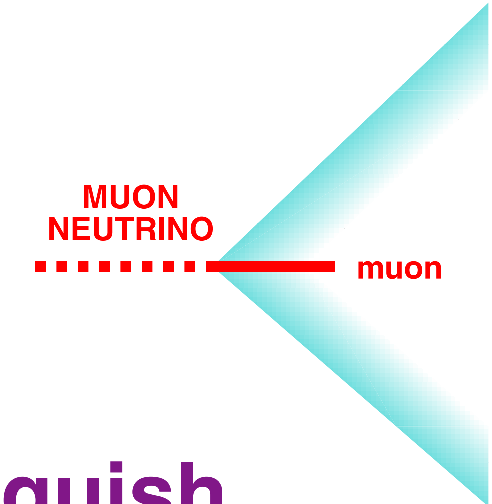
optically isolated veto and shield
1800 20cm pmts recovered from IMB

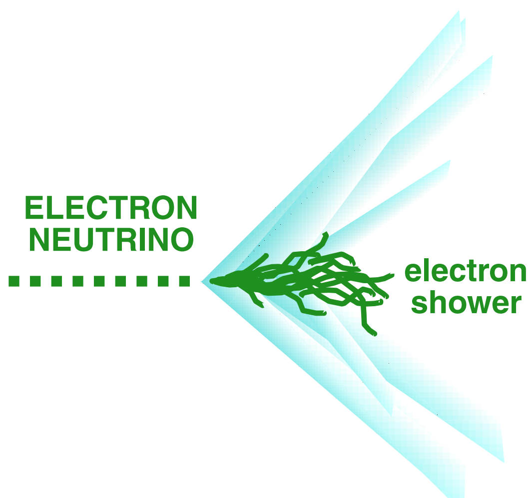
Location

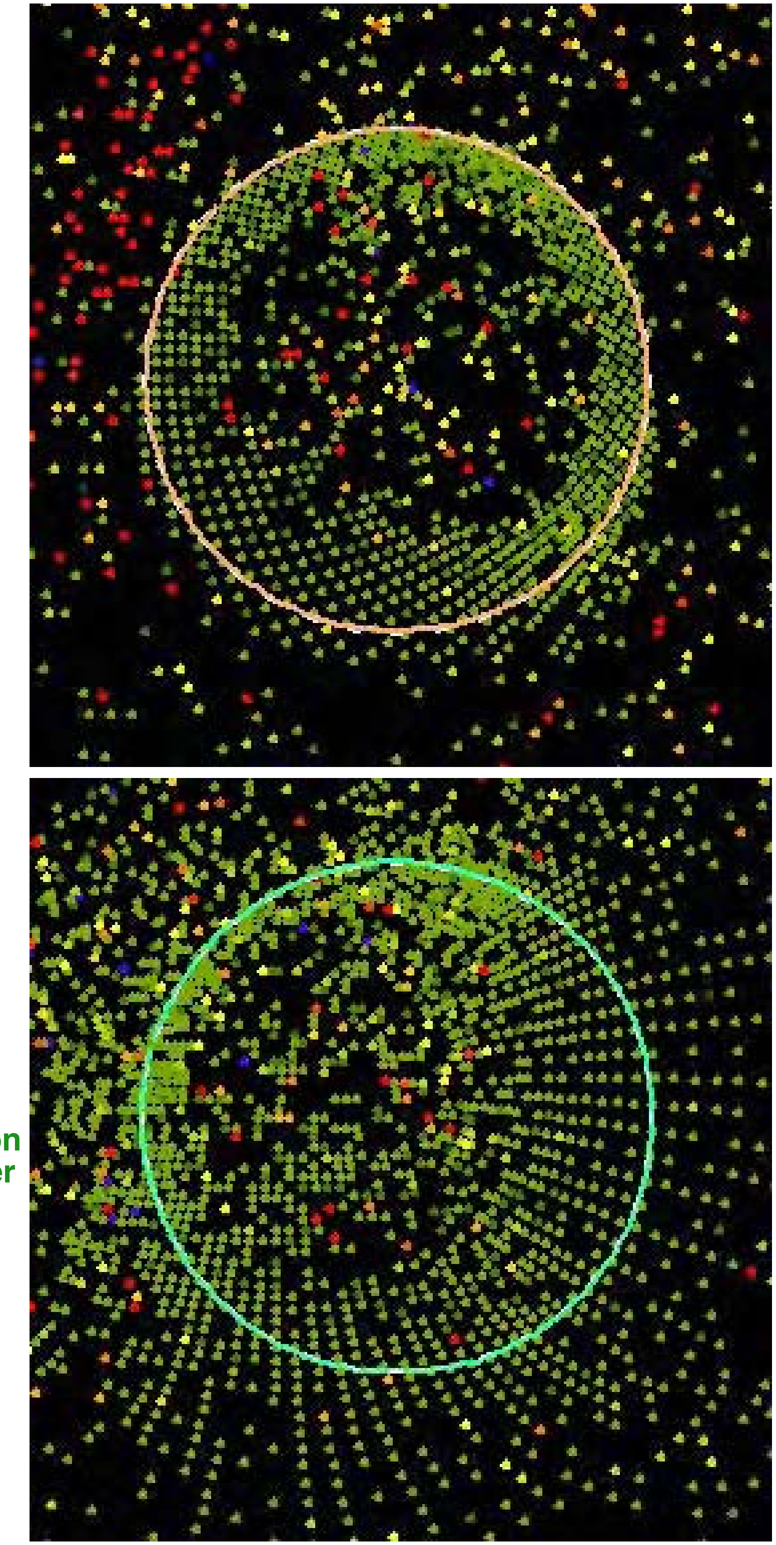
Kamioka zinc mine, Japan
1 km under mountain (2700 m.w.e.)



How to distinguish muon neutrinos from electron neutrinos

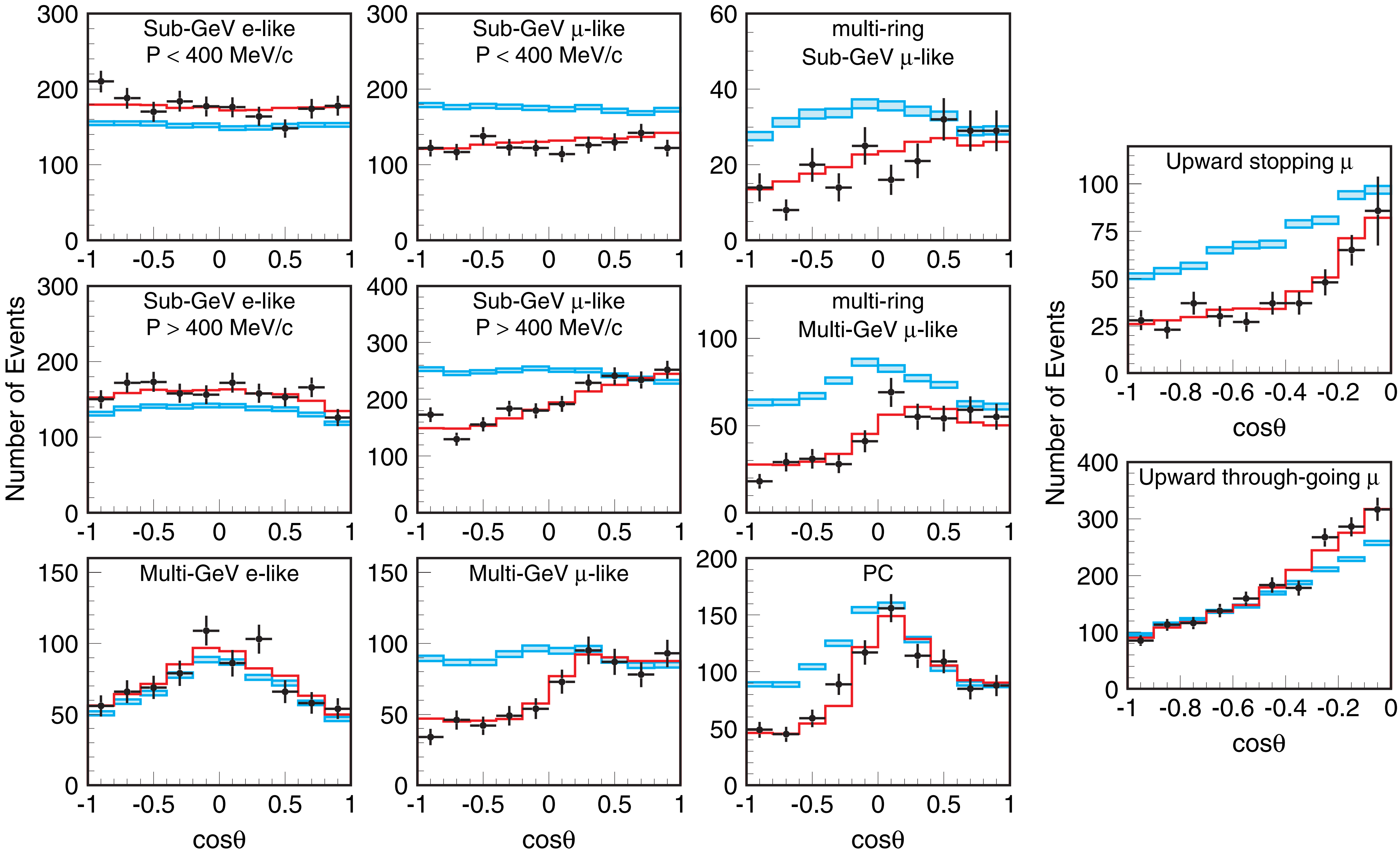




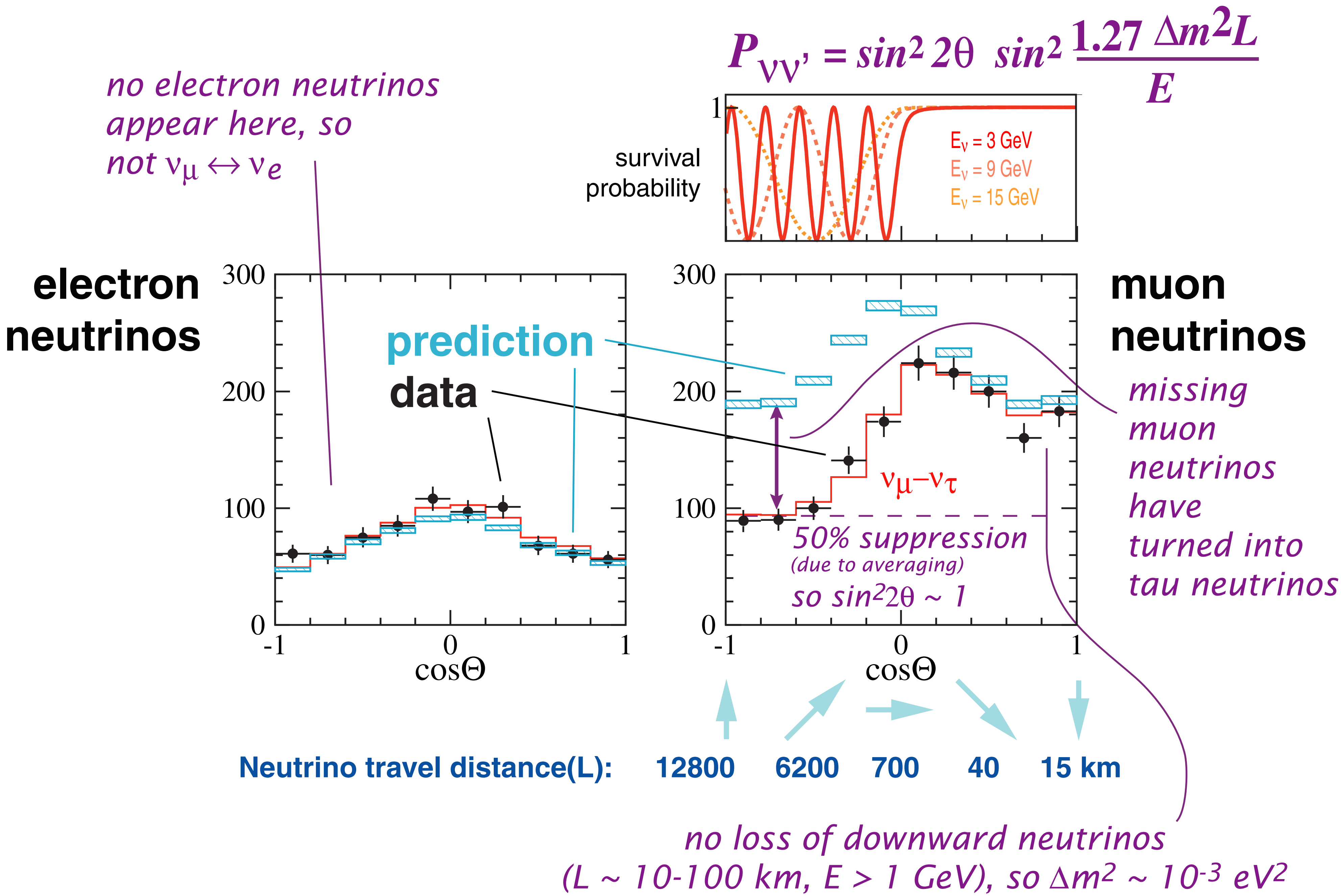


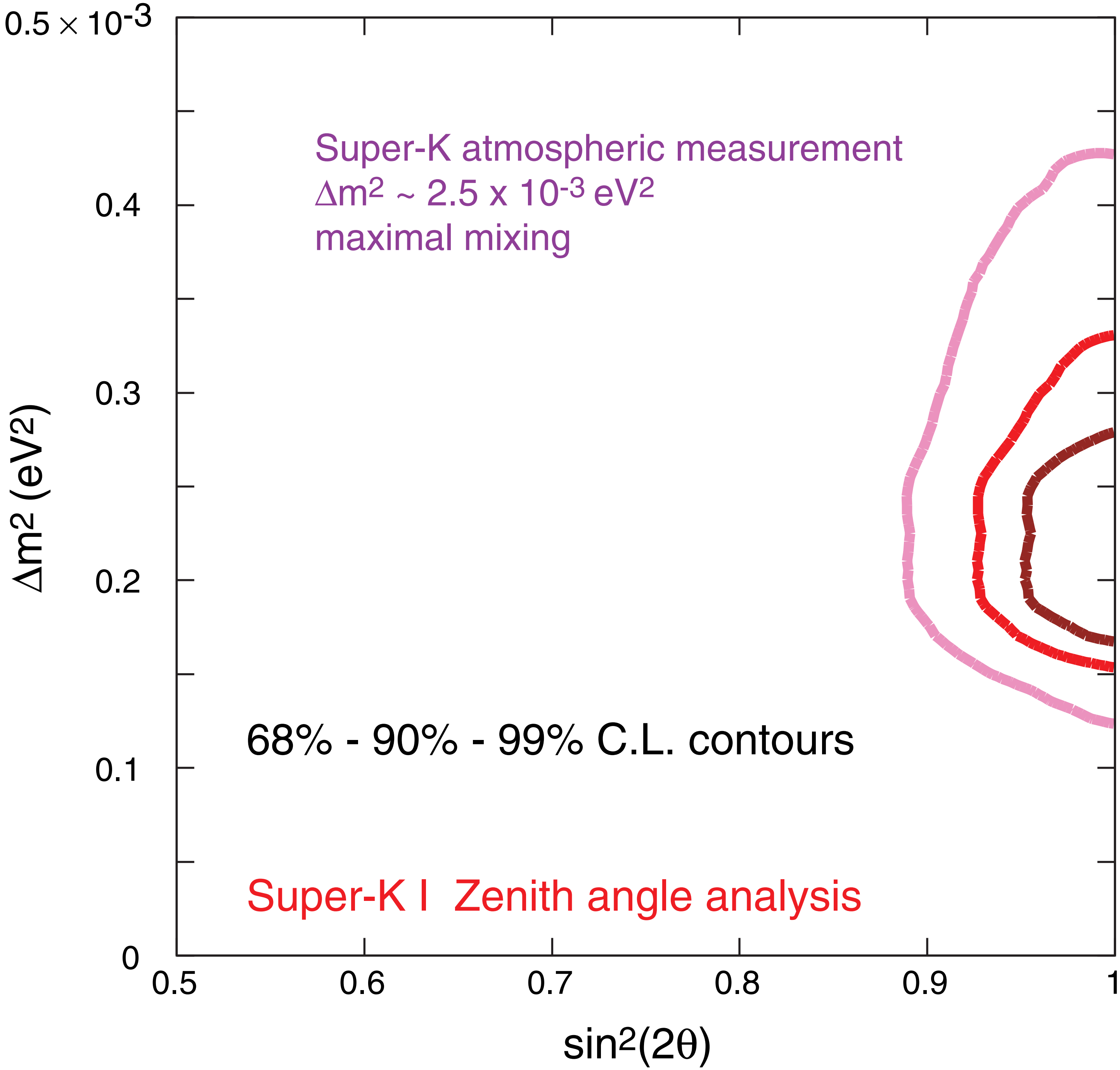
Super-K Atmospheric Neutrino Data

Zenith Angle Distributions



How is this Neutrino Oscillation?

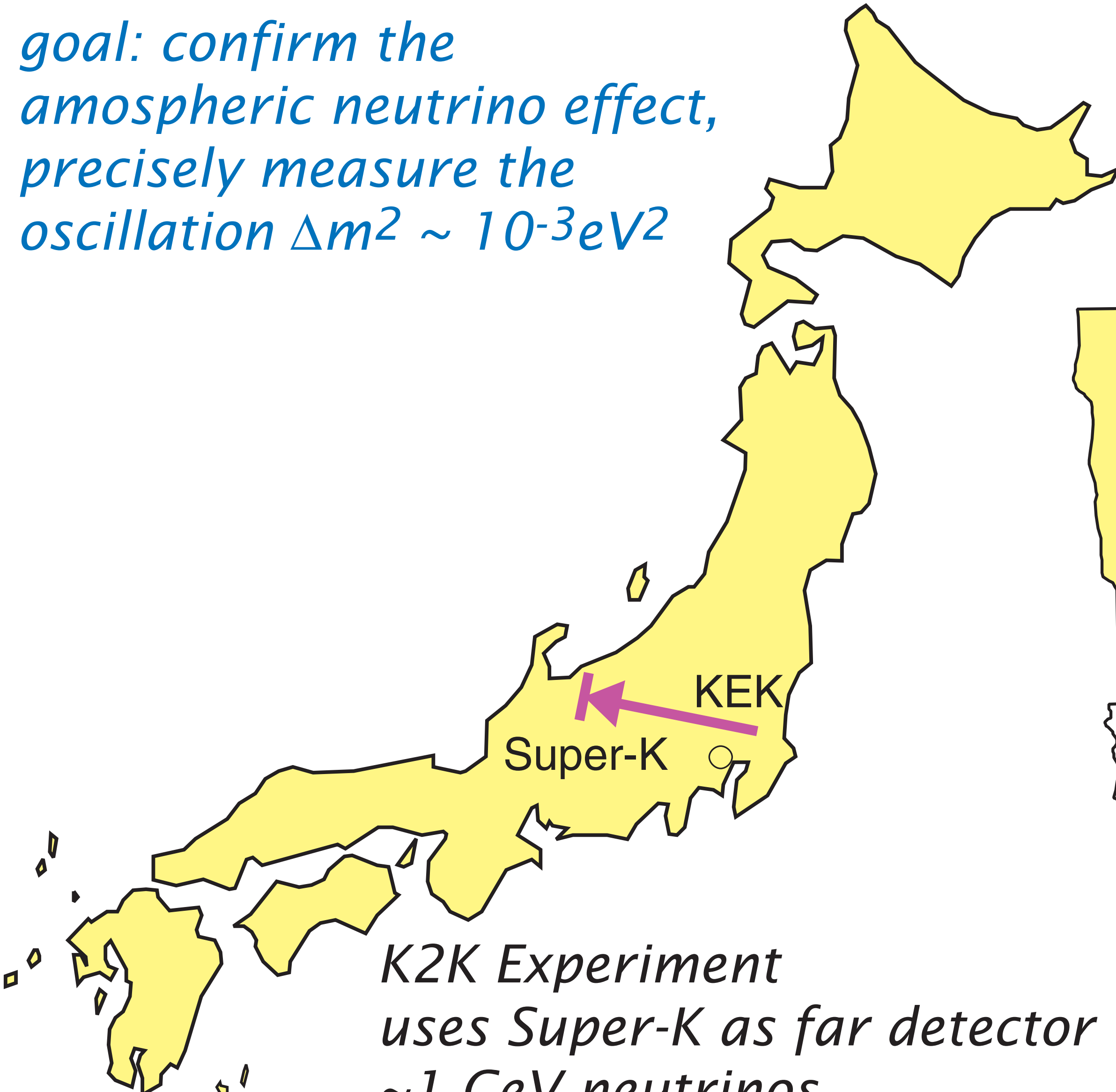




0.5 × 10-3
0.4
0.3
0.2
0.1
0
0.5
0.6
0.7
0.8
0.9
1
Δm2 (eV2)
sin2(2θ)
Super-K atmospheric measurement
Δm2 ~ 2.5 x 10-3 eV2
maximal mixing
68% - 90% - 99% C.L. contours
Super-K I Zenith angle analysis

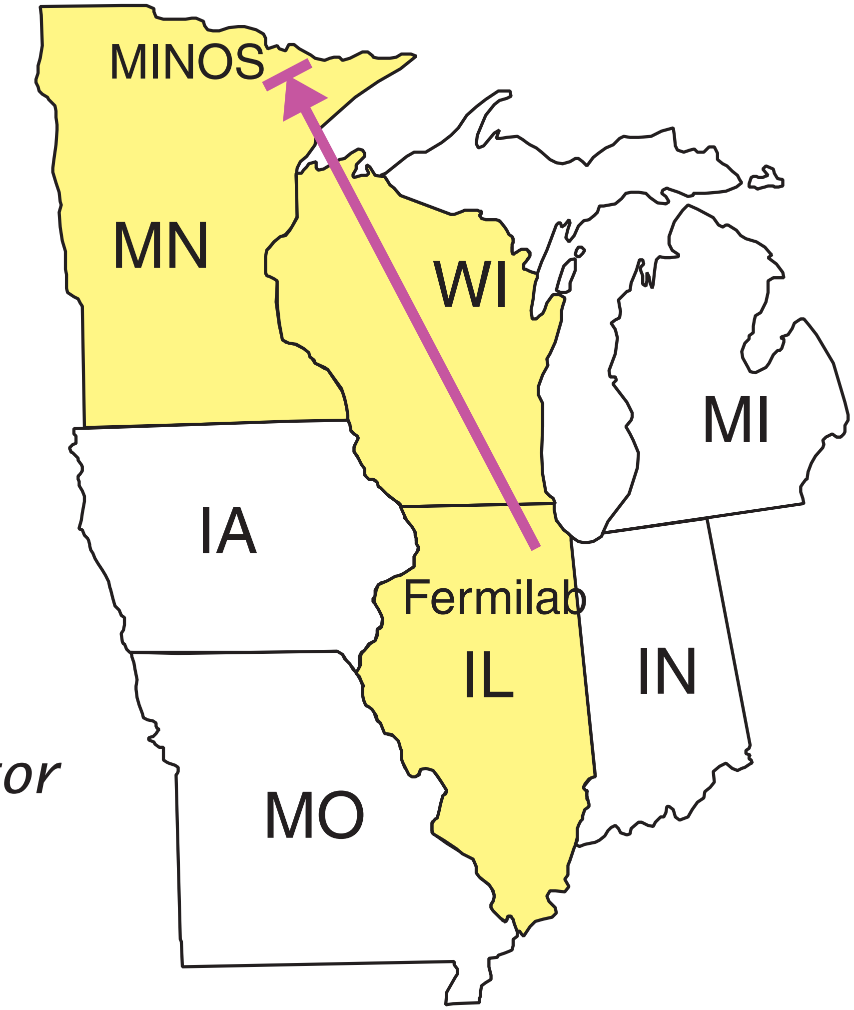
Long Baseline Neutrino Oscillation Experiments

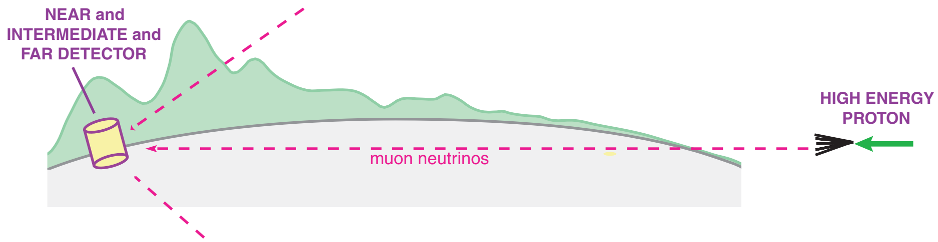
goal: confirm the amospheric neutrino effect, precisely measure the oscillation $\Delta m^2 \sim 10^{-3} eV^2$



K2K Experiment
uses Super-K as far detector
~1 GeV neutrinos
L=250 km
1999-2004

MINOS Experiment
Fermilab to Minnesota
~3 GeV neutrinos
L= 750 km
started in 2005





Atmospheric Neutrinos

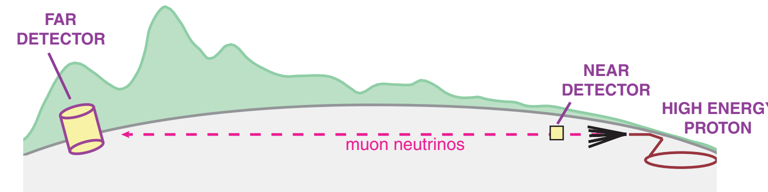
mixed beam of ν_μ $\overline{\nu}_\mu$ ν_e $\overline{\nu}_e$

wide energy band 200 MeV - 1 TeV

continuous flux - free

multiple baselines 10 km - 13000 km

neutrino direction unknown



Long Baseline Neutrinos

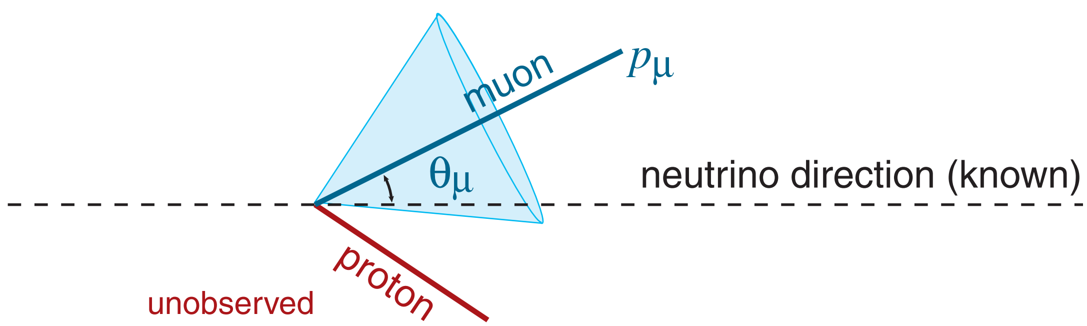
nearly pure beam of ν_μ

narrow energy band, adjustable

pulsed flux - expensive

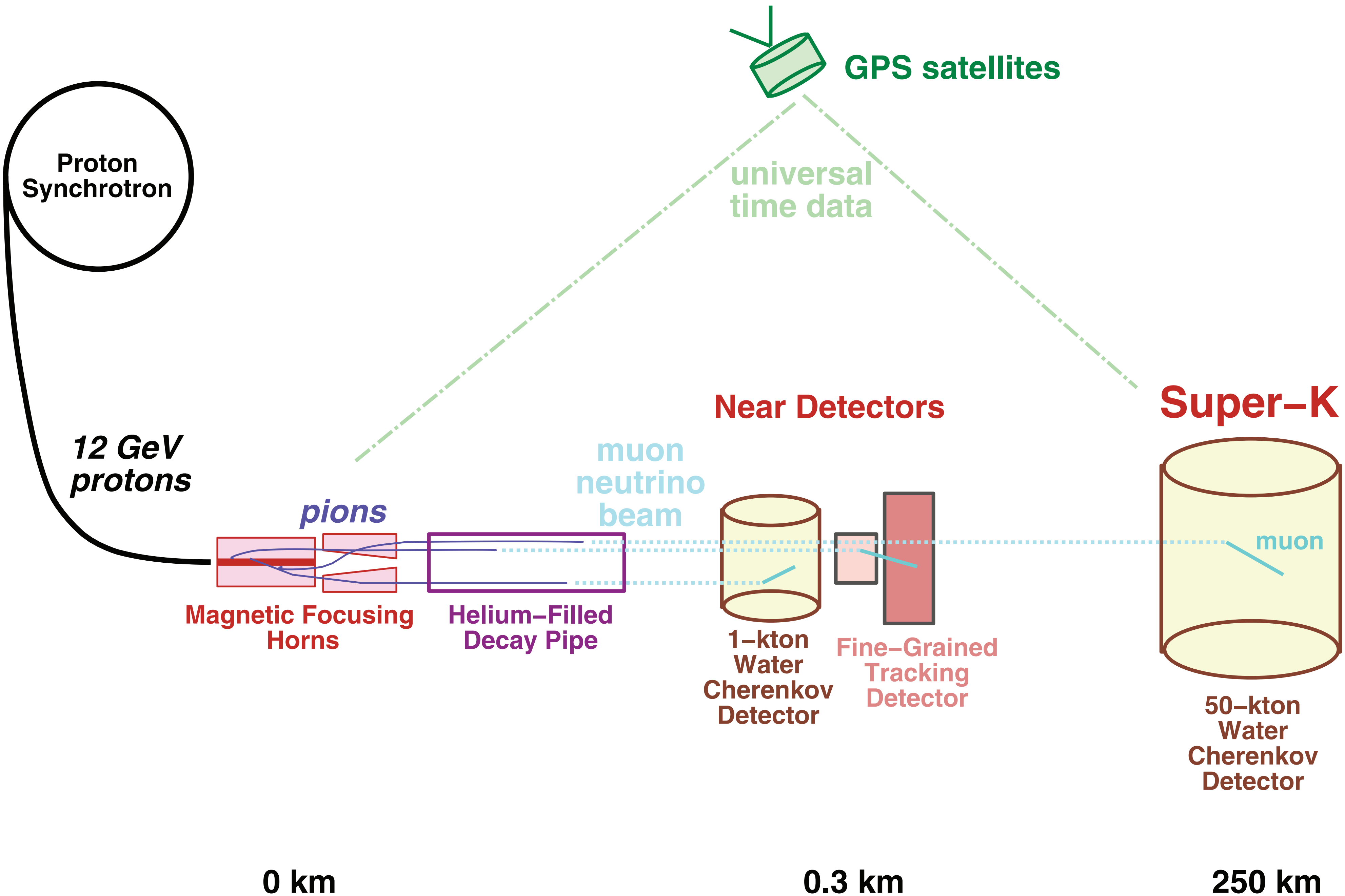
fixed baseline 250 / 750 km so far

neutrino direction known



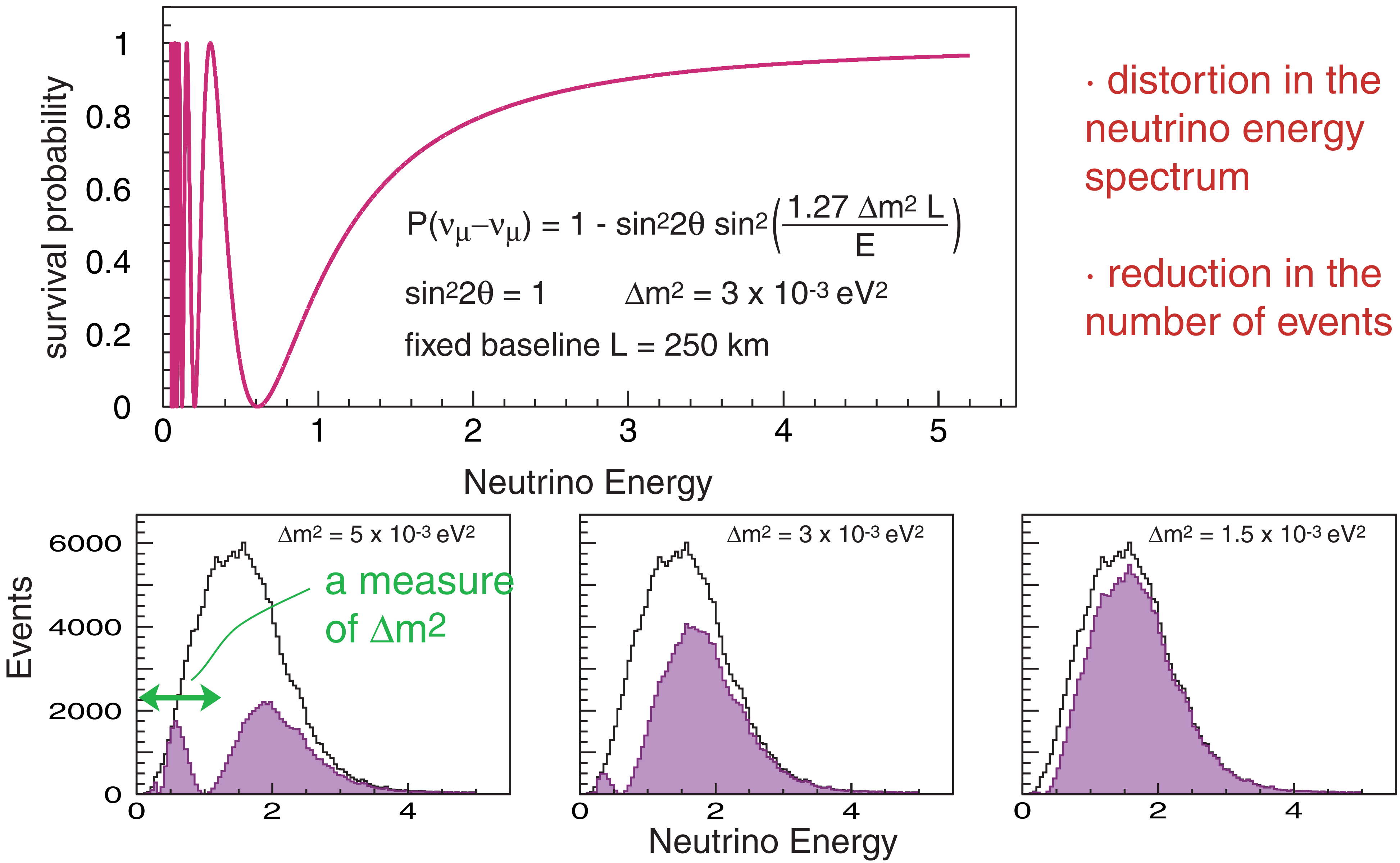
$$E_\nu = \frac{M_n E_\mu - m_\mu^2/2}{M_n - E_\mu + p_\mu \cos\theta_\mu}$$

useful for quasi-elastic events (prevalent at low energies ~1 GeV)



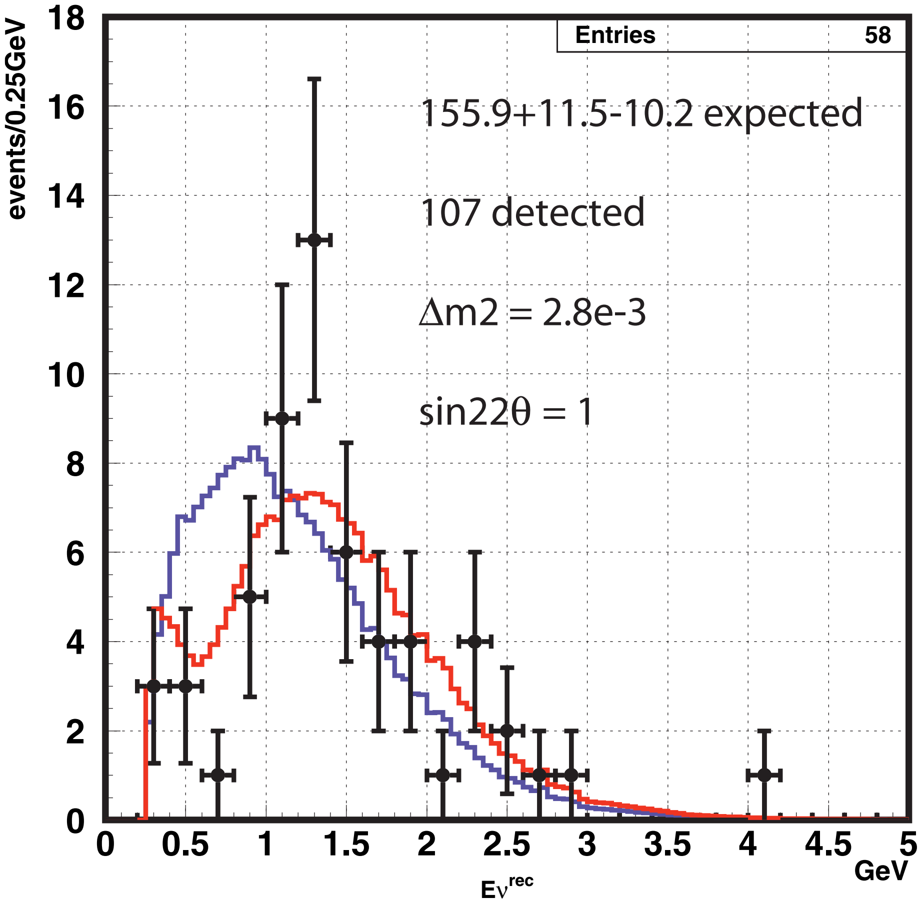
Proton Synchrotron
GPS satellites
universal time data
12 GeV protons
pions
muon neutrino beam
Near Detectors
Super–K
muon
Magnetic Focusing Horns
Helium–Filled Decay Pipe
1–kton Water Cherenkov Detector
Fine–Grained Tracking Detector
50–kton Water Cherenkov Detector
0 km
0.3 km
250 km

Principle of Long Baseline Experiments

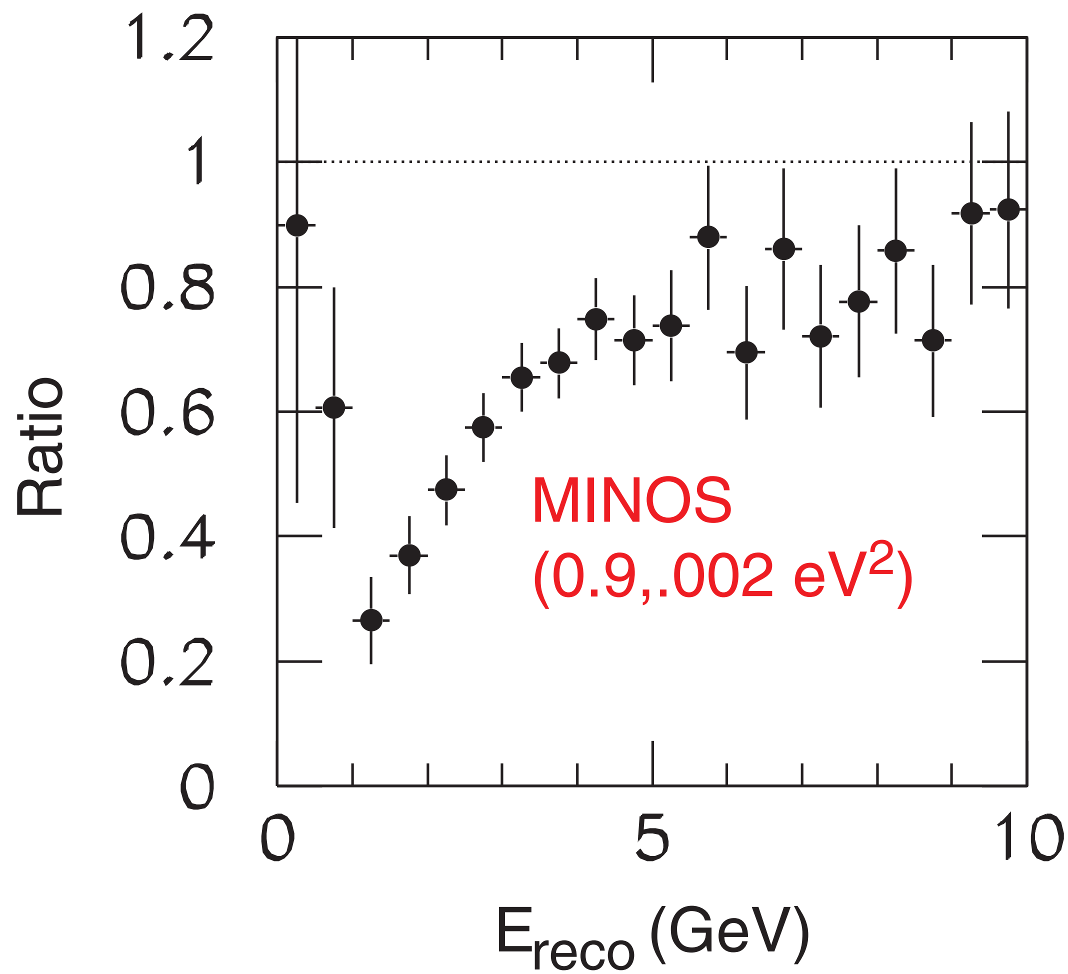


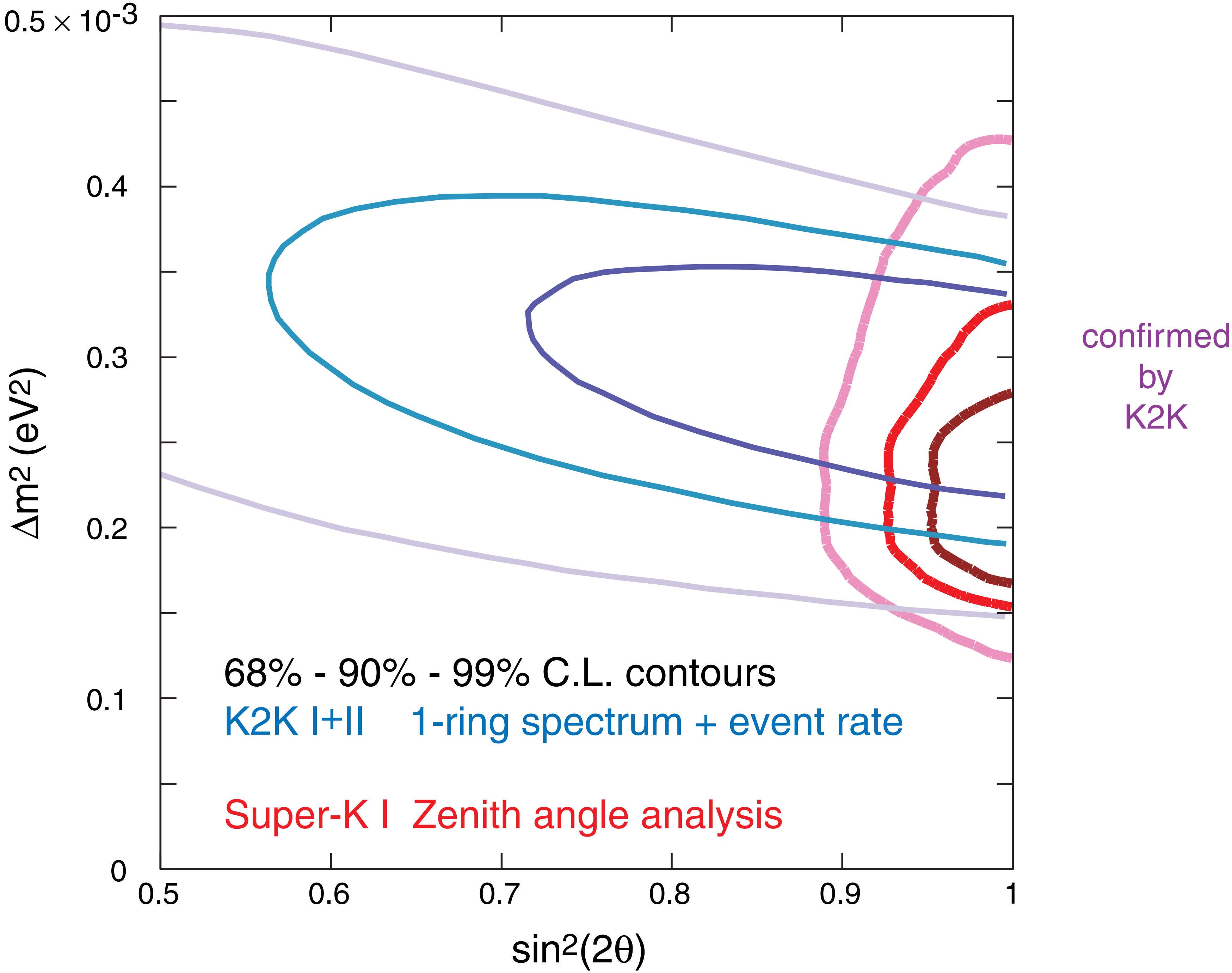
- distortion in the neutrino energy spectrum
- reduction in the number of events

K2K results

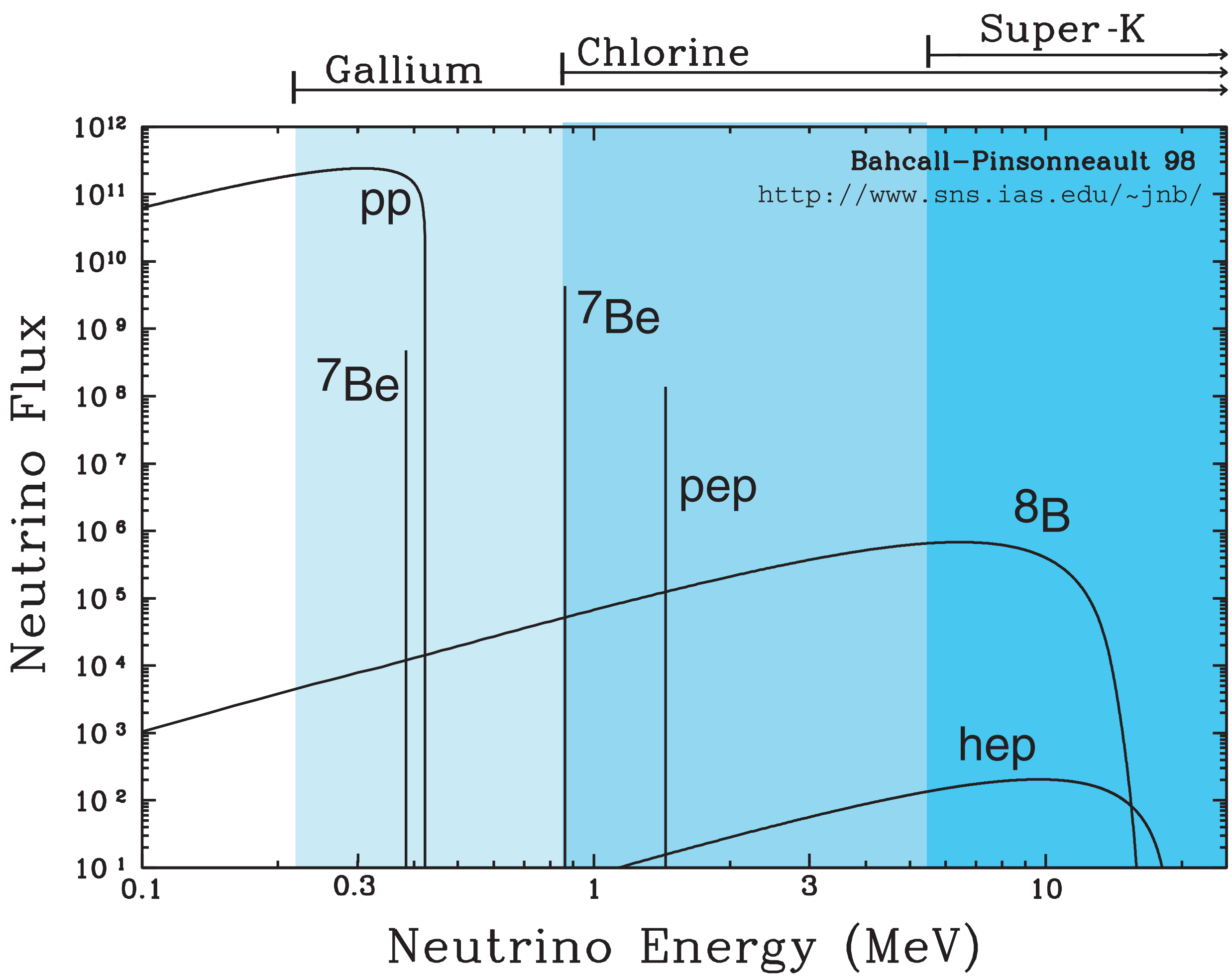


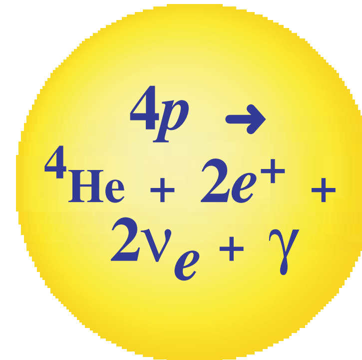
MINOS expectation




0.5 × 10-3
0.4
0.3
0.2
0.1
0
Δm2 (eV2)
0.5
0.6
0.7
0.8
0.9
1
sin2(2θ)
68% - 90% - 99% C.L. contours
K2K I+II 1-ring spectrum + event rate
Super-K I Zenith angle analysis
confirmed
by
K2K

Solar Neutrinos





$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$

pp

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$

Beryllium-7

${}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_e$

Boron-8

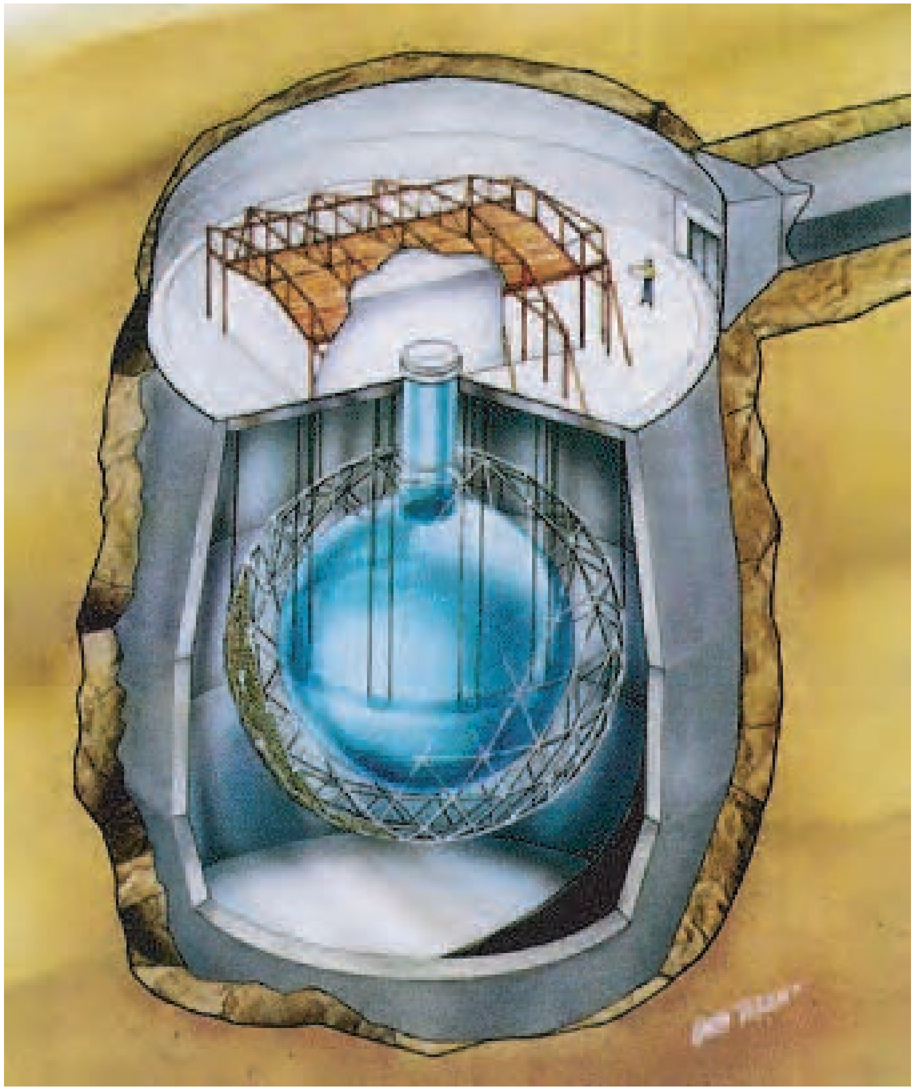
$$\frac{\text{Flux measured}}{\text{Flux predicted}}$$

= 0.58 ± 0.06
Gallium

= 0.33 ± 0.09
Chlorine

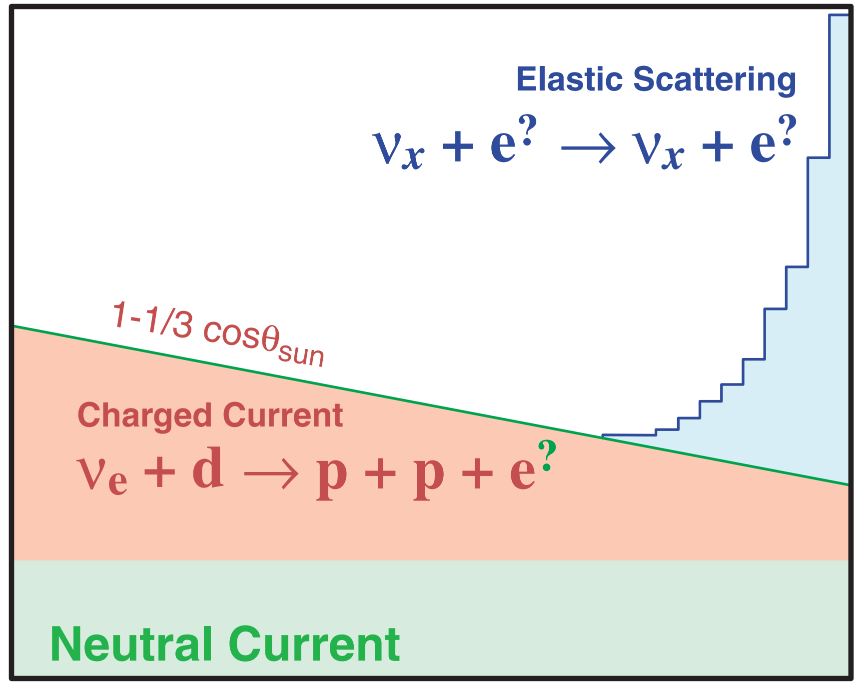
= 0.47 ± 0.01
Water

SNO: Sudbury Neutrino Observatory



- 2073 m underground (~70 cosmic rays/day)
- 1 kton heavy water (D_2O)
- 9500 20-cm photomultiplier tubes
- separately measure ν_e from $\neq \nu_e$

Angle between ν and sun



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

n-capture on d

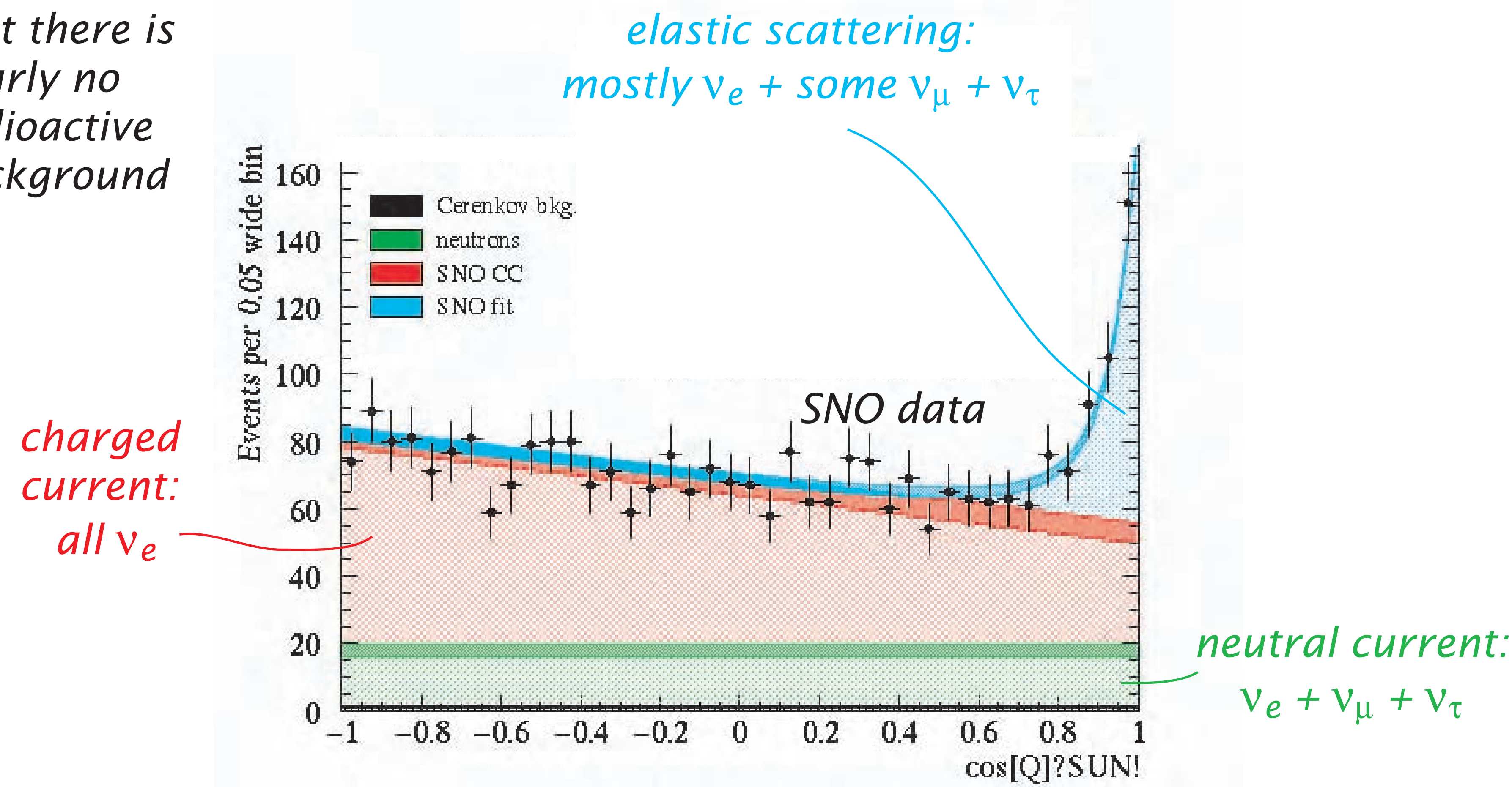
n-capture on Cl
(add MgCl)

n-capture on ^{3}He
(add ^{3}He counters)

x = e or mu or tau

SNO Results

Note!: so deep underground and clean that there is nearly no radioactive background



ν_e only: $\Phi_{CC} = 1.68^{+0.06}_{-0.06}(stat.)^{+0.08}_{-0.09}(sys.)\times 10^6 cm^{-2}s^{-1}$

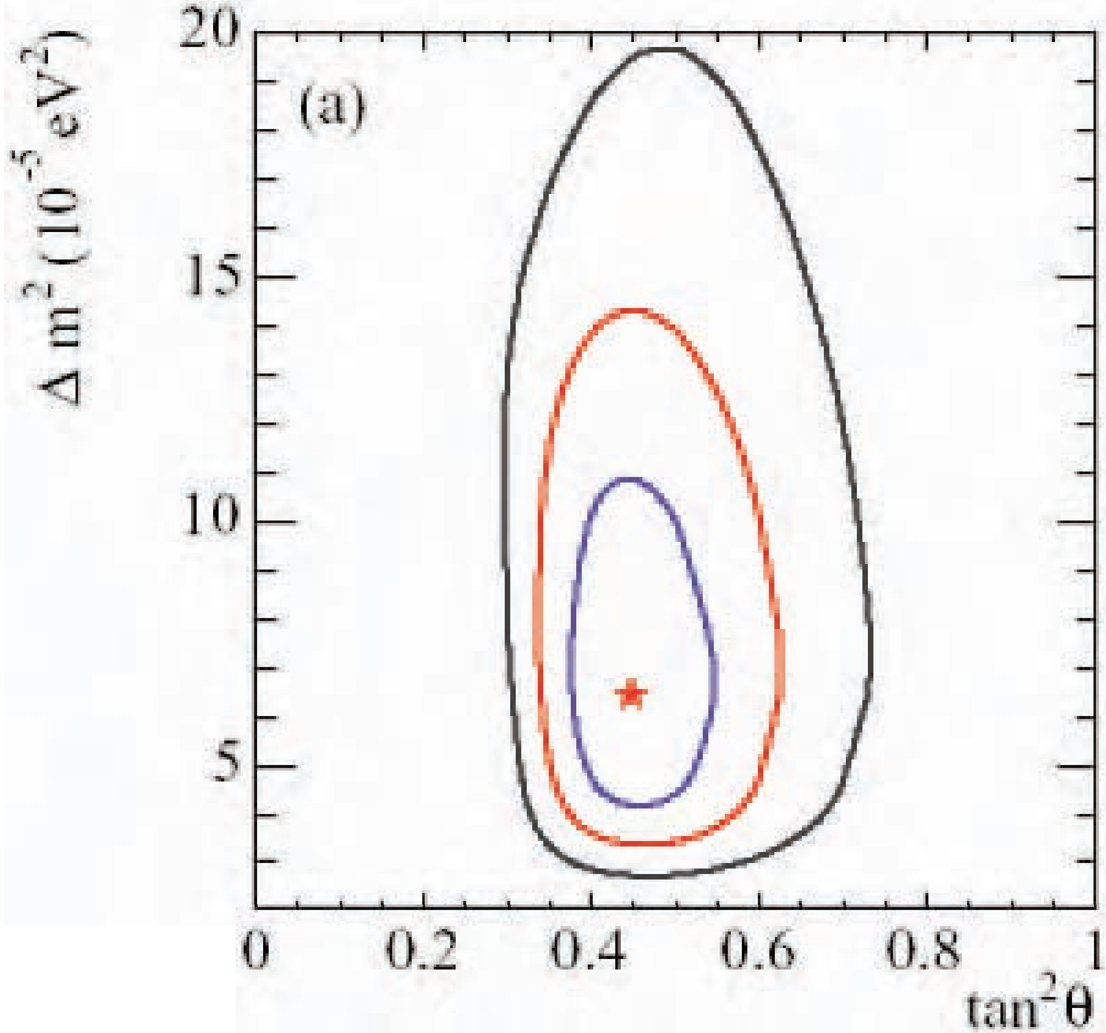
$\Phi_{ES} = 2.35^{+0.22}_{-0.22}(stat.)^{+0.15}_{-0.15}(sys.)\times 10^6 cm^{-2}s^{-1}$

$\nu_e + \nu_\mu + \nu_\tau$: $\Phi_{NC} = 4.94^{+0.21}_{-0.21}(stat.)^{+0.38}_{-0.34}(sys.)\times 10^6 cm^{-2}s^{-1}$

$\neq$

$\Phi_{BP04} = 5.82 \pm 1.34 \times 10^6 cm^{-2}s^{-1}$

Solar Result
(SNO+SK+Homestake+GNO+GALLEX+SAGE)



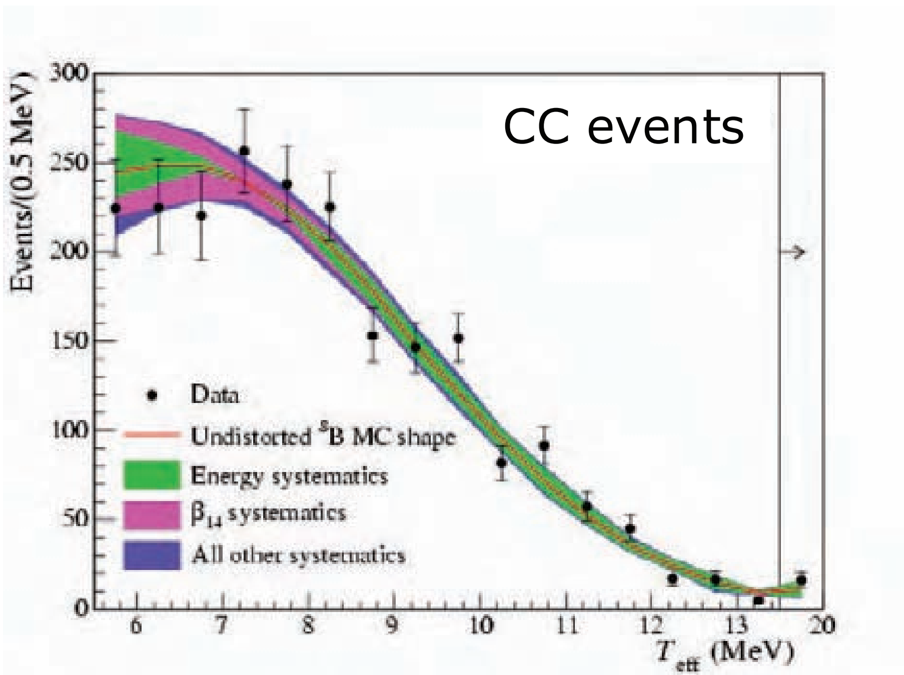
$$\Delta m^2_{12} = 6.5^{+4.4}_{-2.3} \times 10^{-5} \, eV^2$$

$$\tan^2\theta_{12} = 0.45^{+0.09}_{-0.08}$$

large mixing
(but not maximal)

Where's the Smoking MSW Gun?

(besides SNO's NC/CC of course)

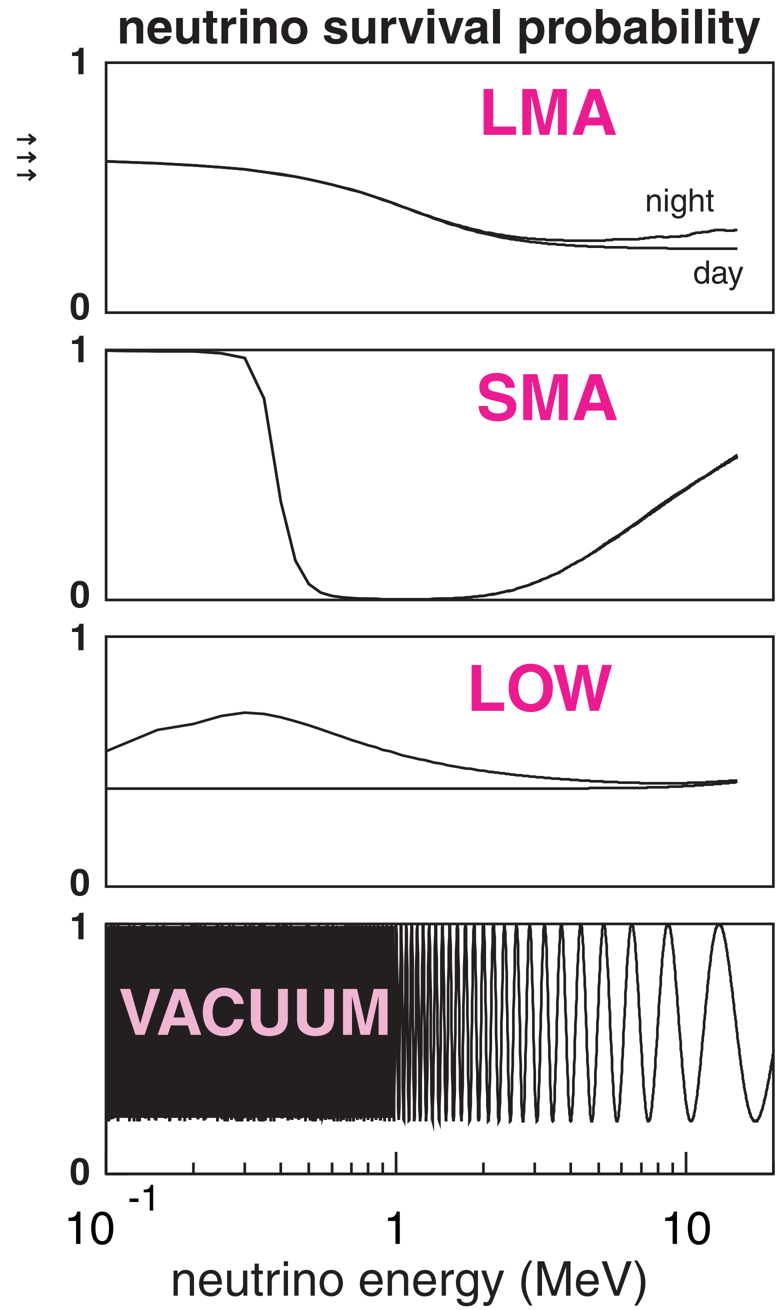


SK also sees no significant spectral distortion

$$\text{SK day/night asymmetry} = 0.021 \pm 0.020$$

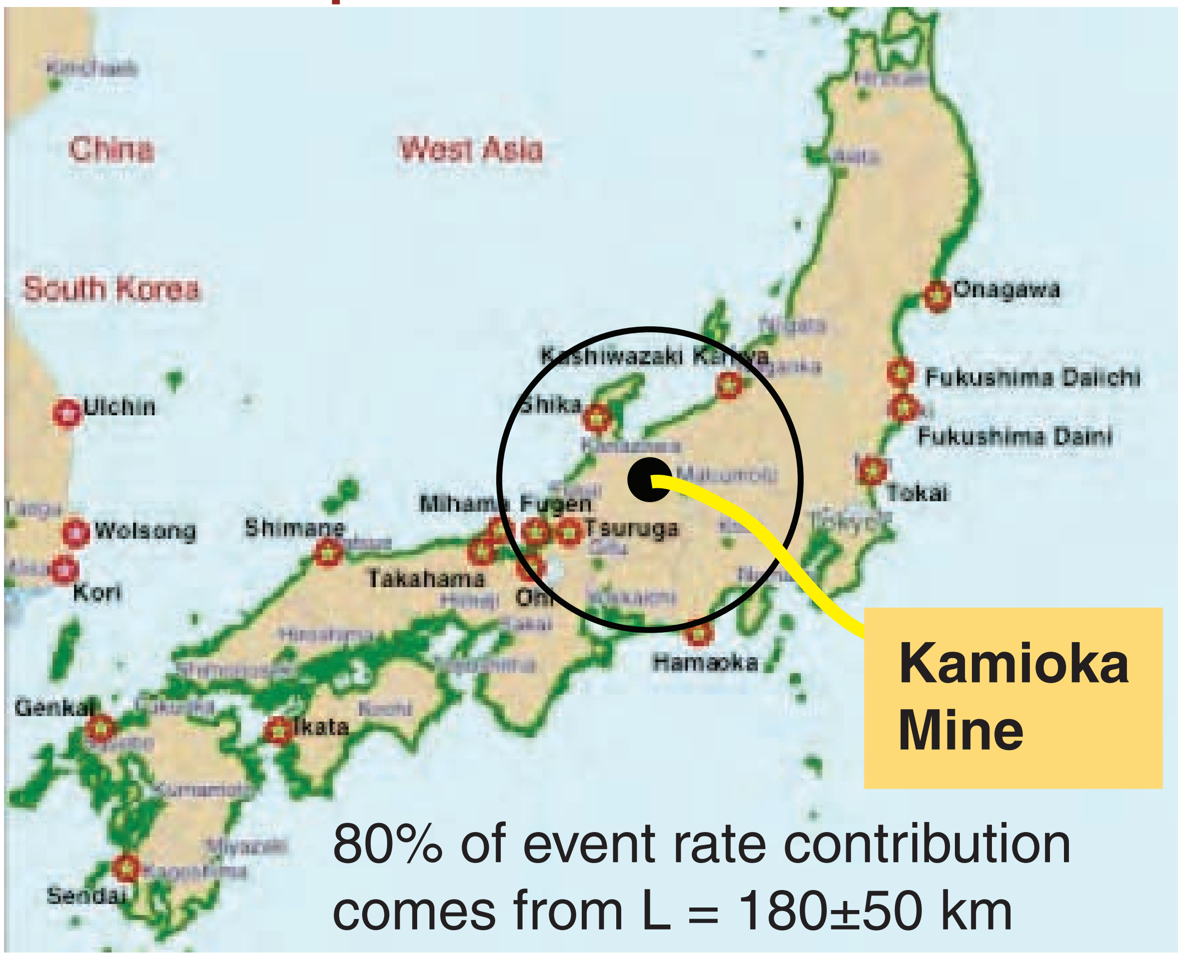
$$\text{SNO day/night asymmetry} = 0.037 \pm 0.040$$

no seasonal variation except $1/r^2$

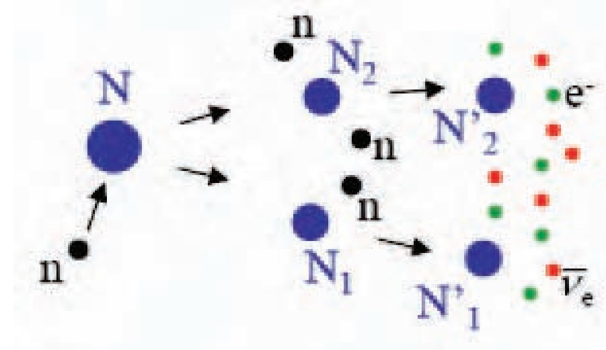


KamLAND Reactor Experiment

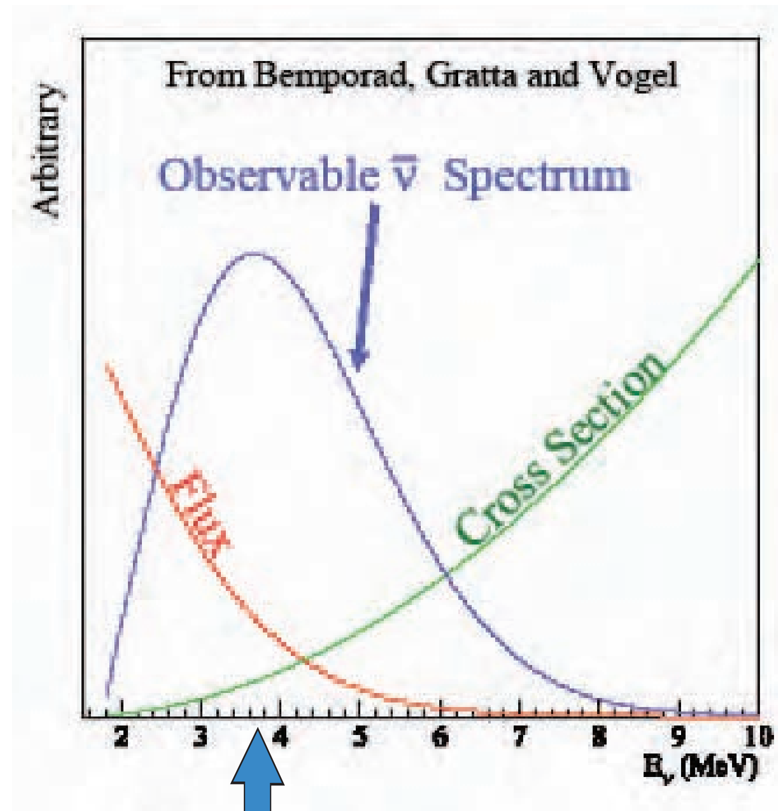
Japanese Power Reactors



80% of event rate contribution comes from L = 180±50 km

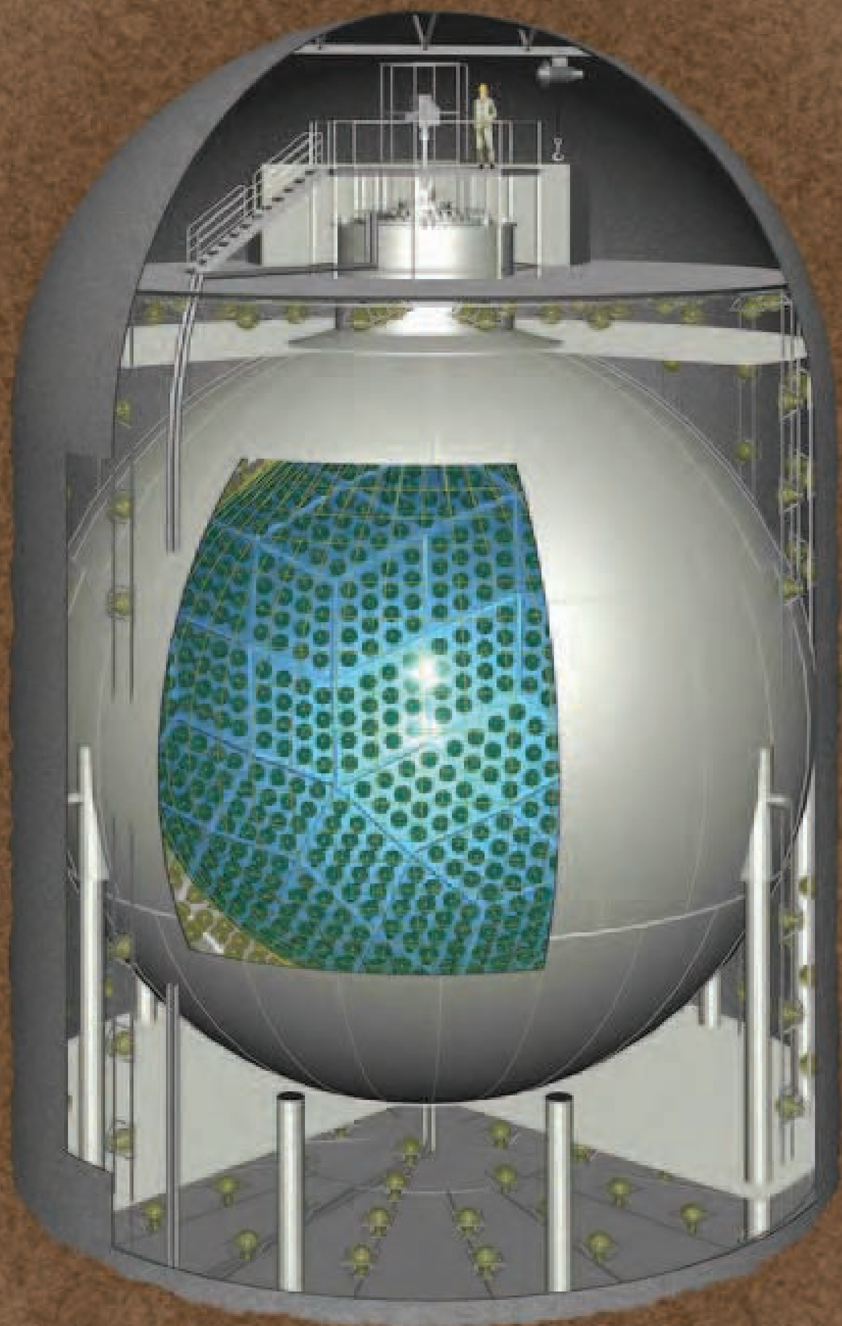


~6 $\overline{\nu}_e$ /fission



E ~ 3.7 MeV

KamLAND Detector



1000 ton liquid scintillator
in plastic balloon
surrounded by mineral oil
viewed by 1879 PMTs
in stainless steel sphere
shielded by active water Cherenkov

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

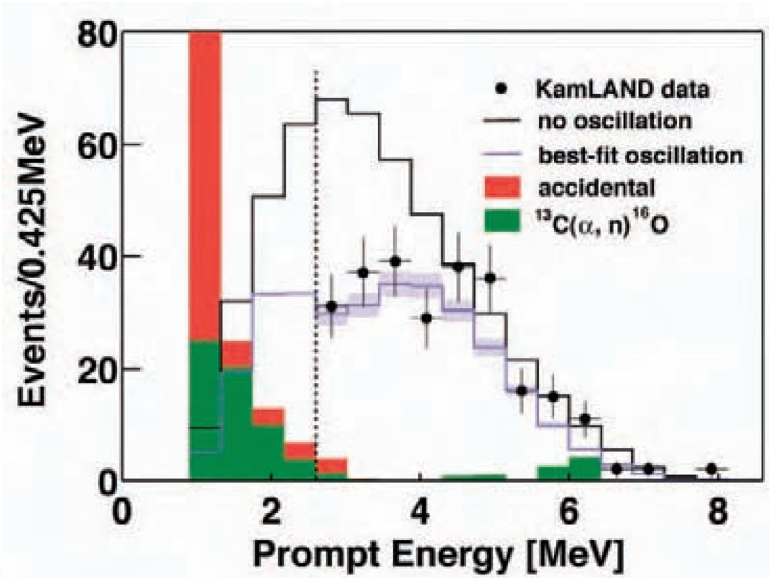
$E_{thresh} = 1.8$ MeV

$$n + p \rightarrow d + \gamma(2.2\ \text{MeV})$$

$\tau \sim 210\ \mu$sec

~1000 events/yr

KamLAND Results

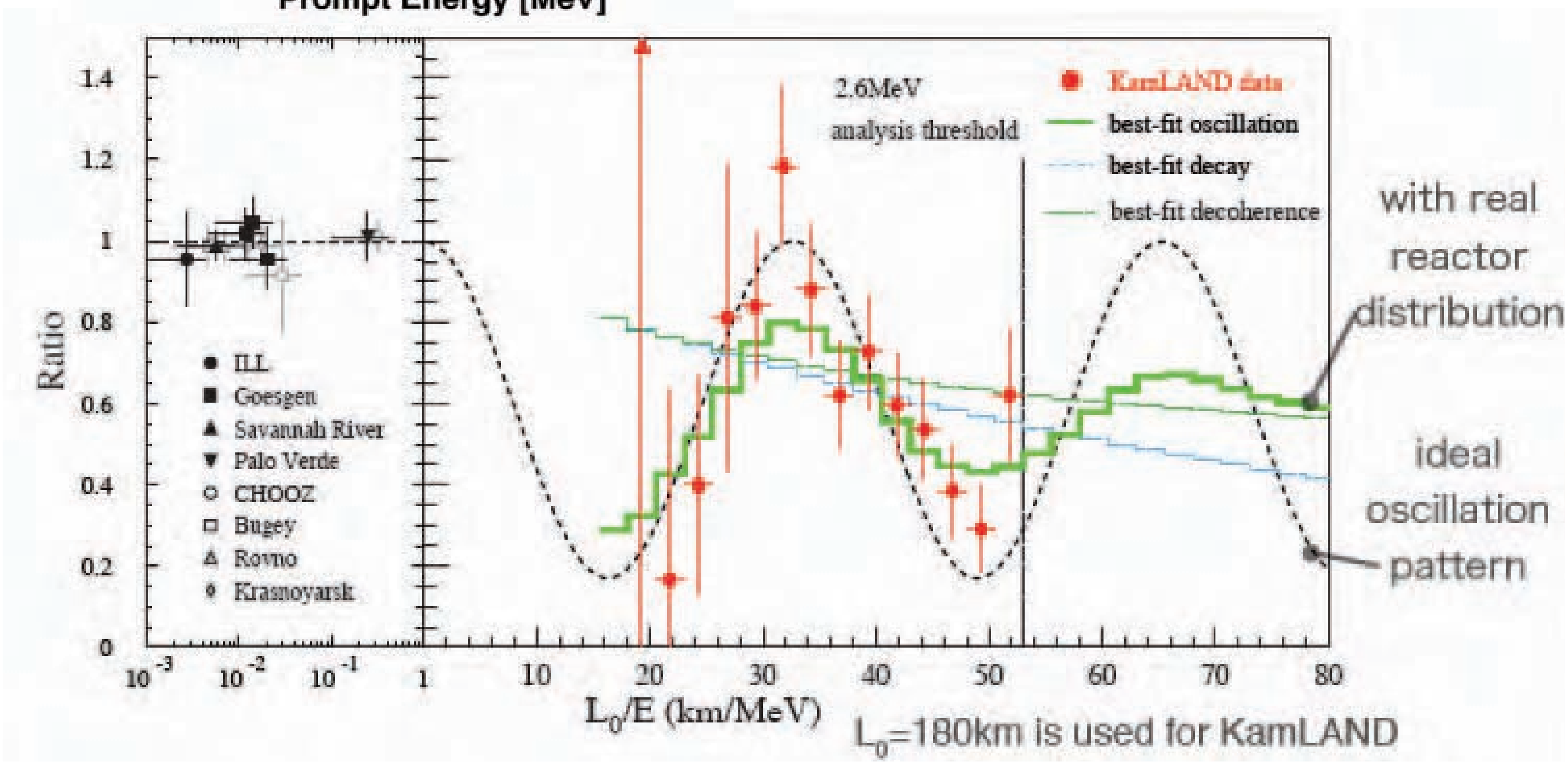


expected = 365.2±23.7 events
observed = 258 events
background = 17.8±7.3 events

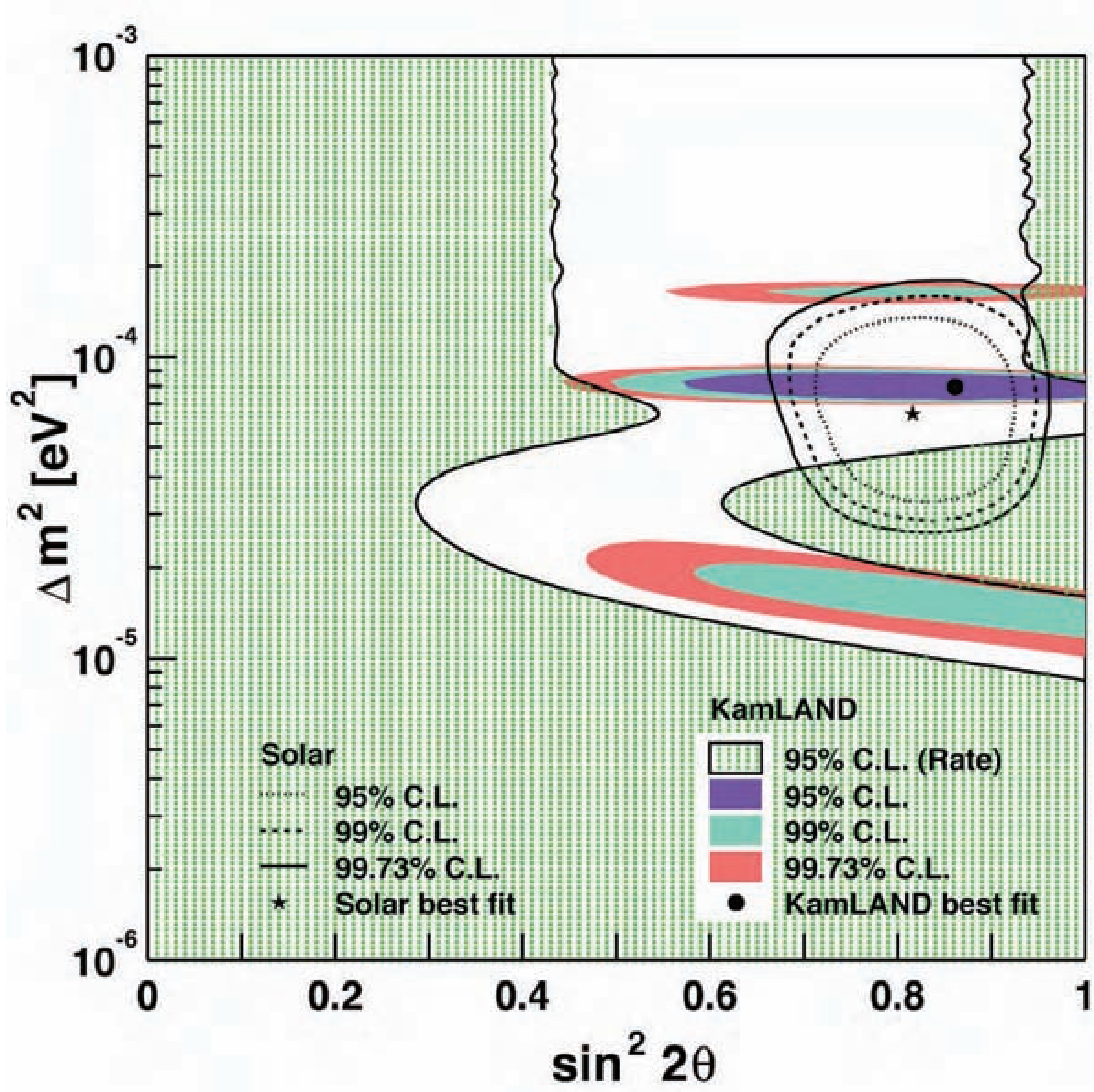
best fit:

$$\Delta m^2 = 7.9\times10^{-5}\ \mathrm{eV}^2$$

$$\sin^2 2\theta = 0.863$$

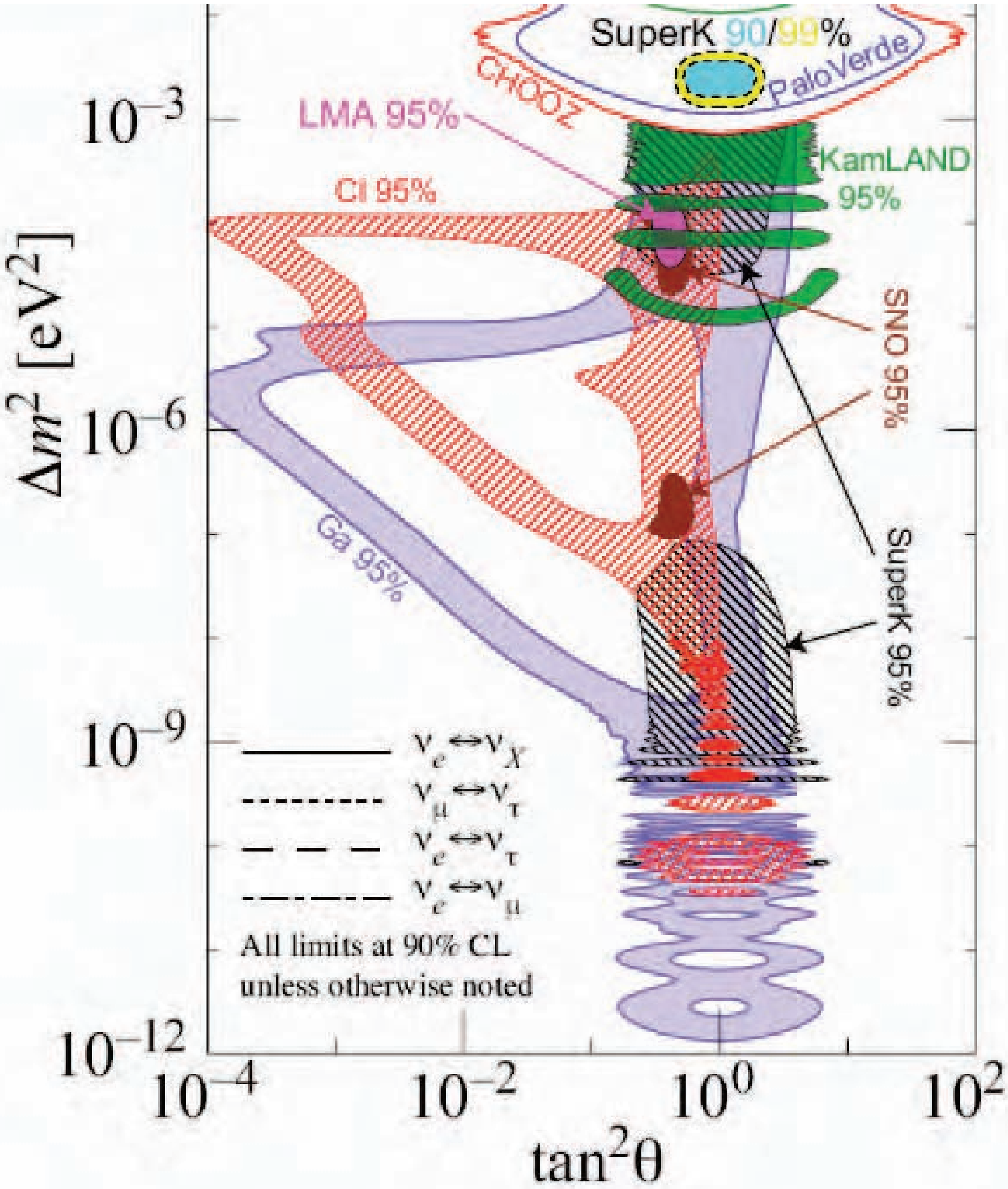


KamLAND compared with Solar

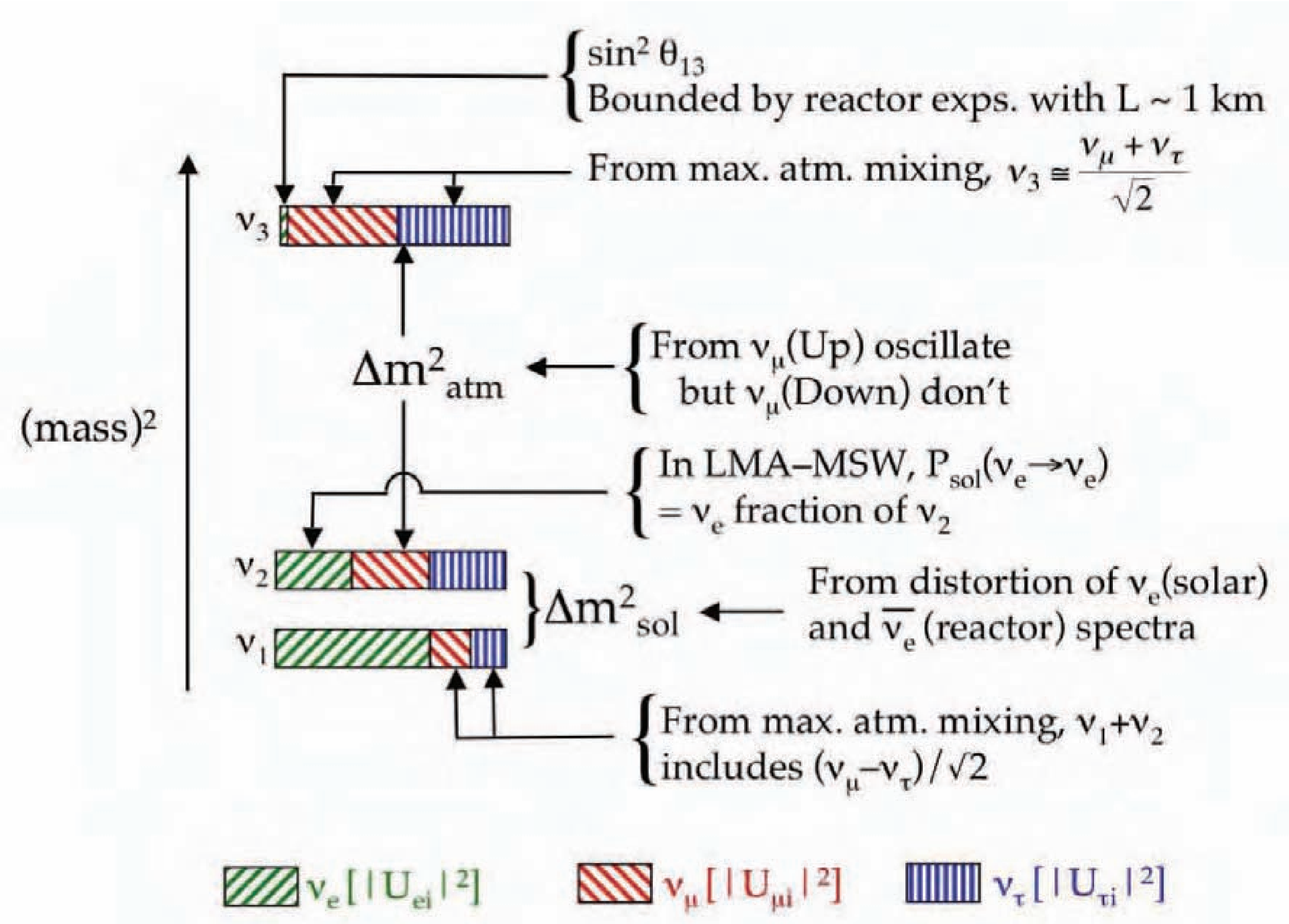


KamLAND measurement is based on vacuum oscillation;
solar survival probability relies on matter effect. Important comparison!

IF YOU CAN UNDERSTAND THIS PLOT YOU ARE STANDING TOO CLOSE



Current Picture of Neutrino Mass and Mixing



B. Kayser hep-ph/0506165

A Useful Parametrization of the PMNS Matrix

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

$\theta_{23} \sim \theta_{atm.} \approx 45^\circ$ $\quad$ $\theta_{13} < 12^\circ$ $\quad$ $\theta_{12} \sim \theta_{solar} \approx 32^\circ$

δ is totally unknown

why is it like this ???

$$U_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix} \qquad U_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

quarks $\qquad$ ***neutrinos***

What We Do Not Yet Know

- Are there only three neutrino states? (LSND)
- Can we really make an appearance experiment?
- What is the absolute mass scale?
- Are neutrinos their own antiparticle? (Majorana)
- What is the sign of the large Δm^2? (heirarchy or)
- What is the value of θ_{23}? Is it truly maximal?
- What is the value of θ_{13}? Is it really zero?
- What is the value of δ?

What We Do Not Yet Know

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  GUTs like this! — $0\nu\beta\beta$ expts wish for this.

- What is the value of θ_{23}? Is it truly maximal?

  GUTs want to know!

- What is the value of θ_{13}? Is it really zero?

  must be > 0 to see CP violation

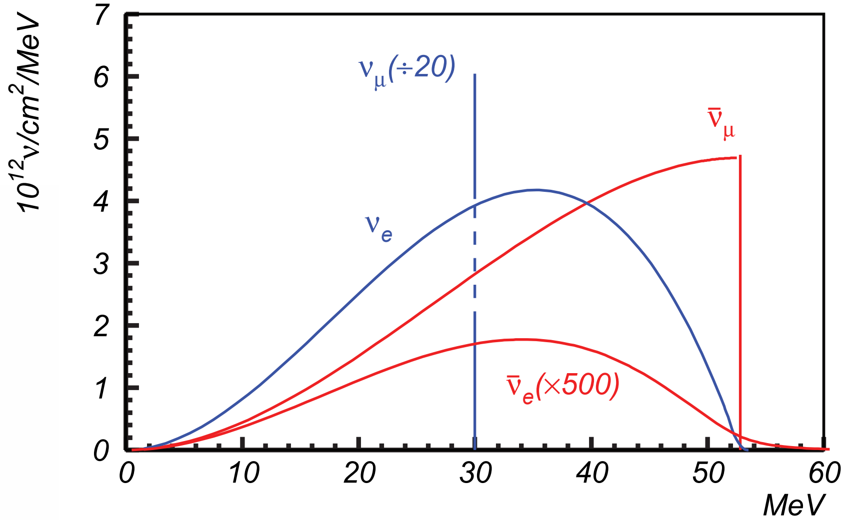
- What is the value of δ? CP violation!

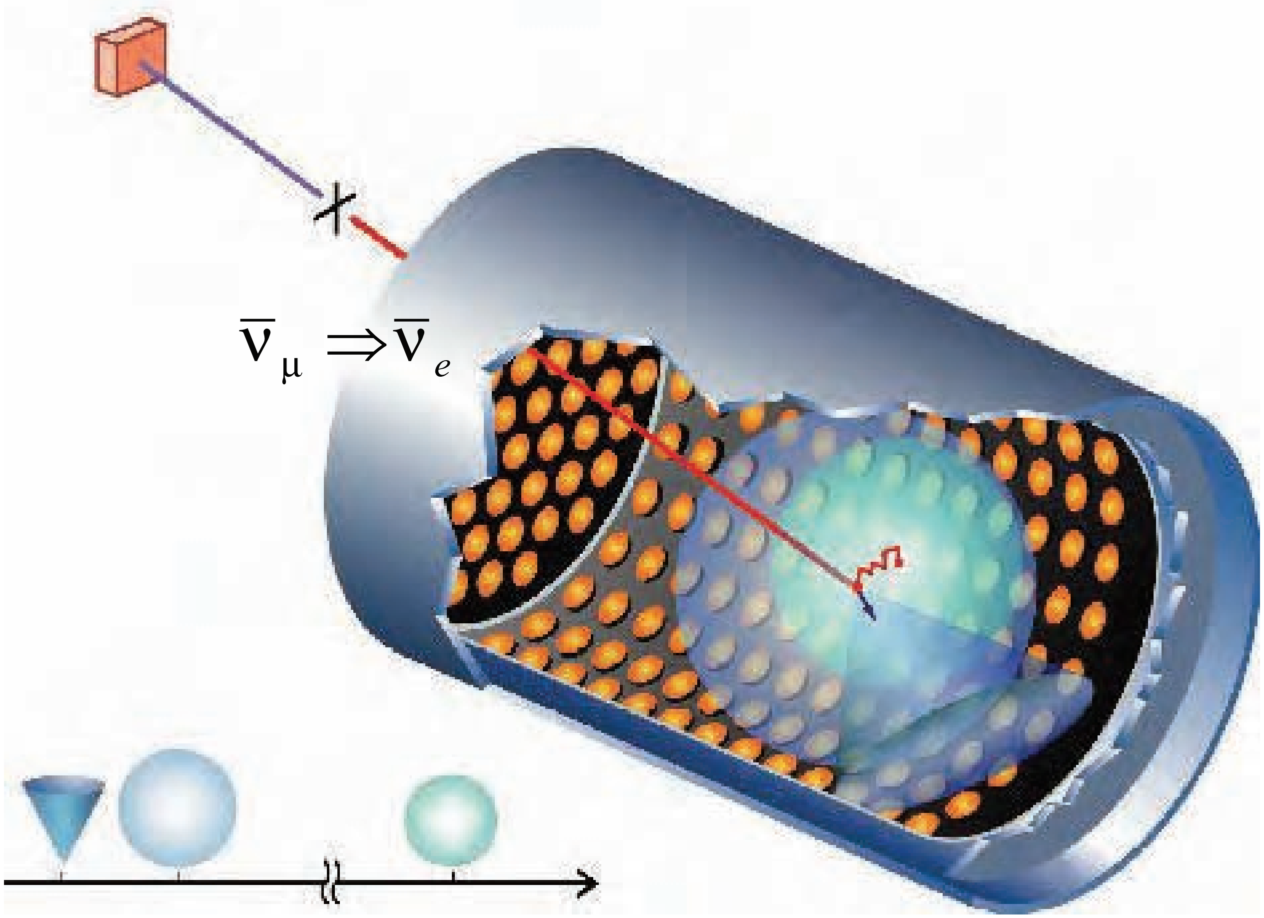
$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

LSND Experiment

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

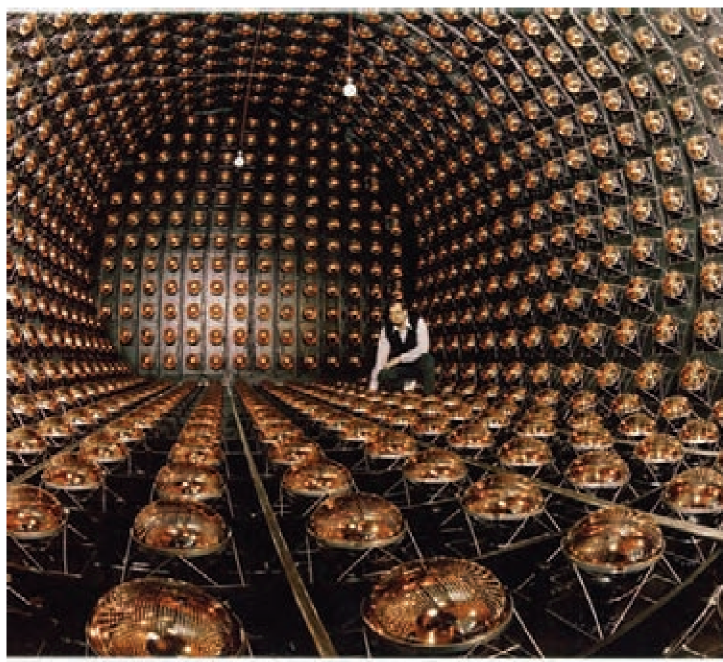
stopped pion beam ⇒
decay-at-rest spectra:





fast response from Cherenkov light from e+
slower response from scintillation light from e+
delayed capture of neutron gives 2.2 MeV gamma

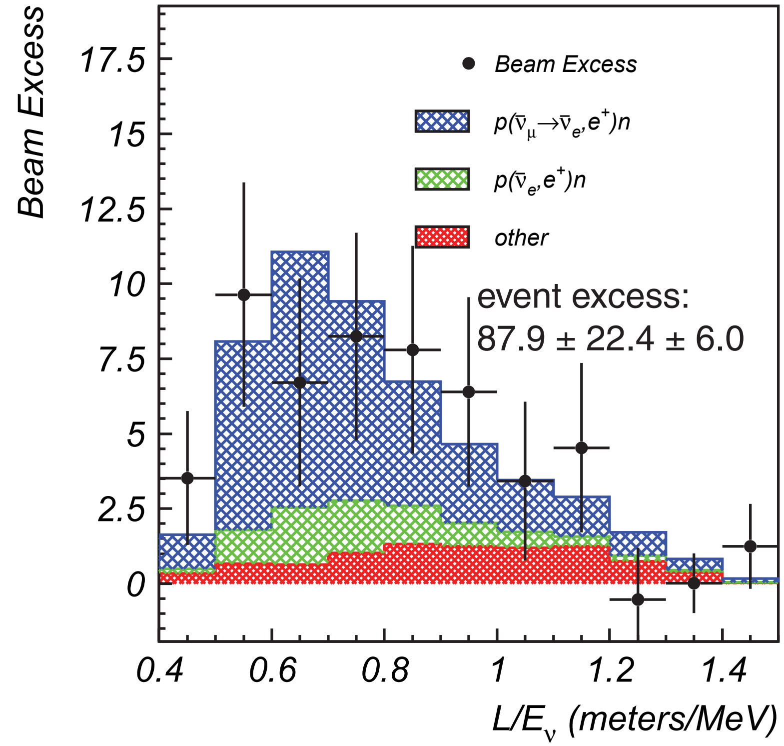
$$\bar{\nu}_e + p \to e^+ + n$$
$$n + p \to d + \gamma\,(2.2\ \mathrm{MeV})$$

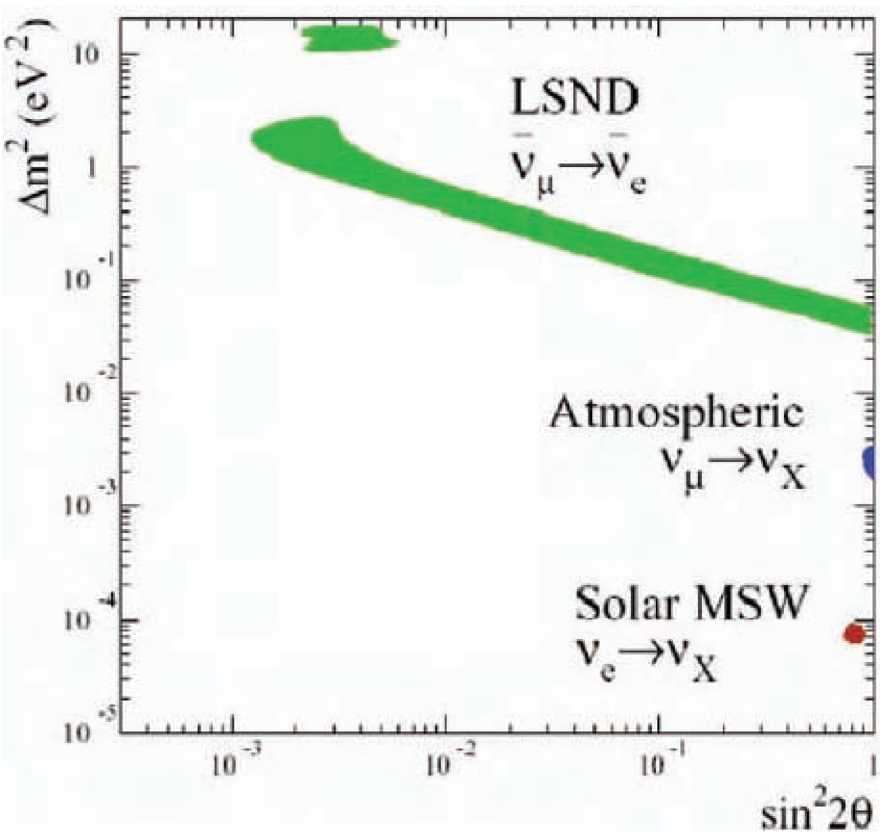


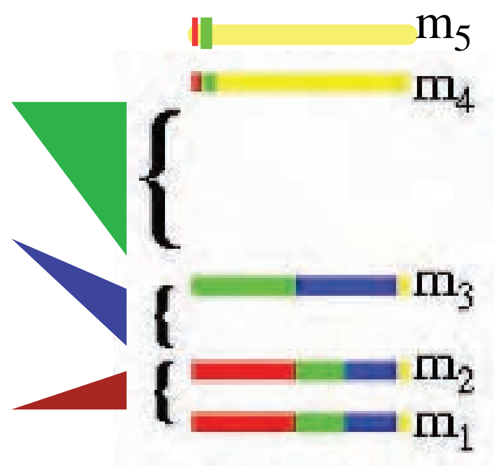
LSND Result

a fourth oscillation signature (with active neutrinos!) is a problem

will be tested by mini-BooNE this year



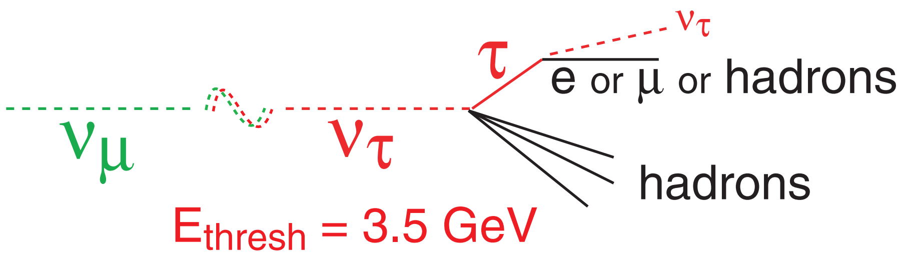




$$\Delta m_{ij}^2 \equiv m_j^2 - m_i^2$$

$$\Delta m_{13}^2 = m_{12}^2 + m_{23}^2$$

Tau Appearance

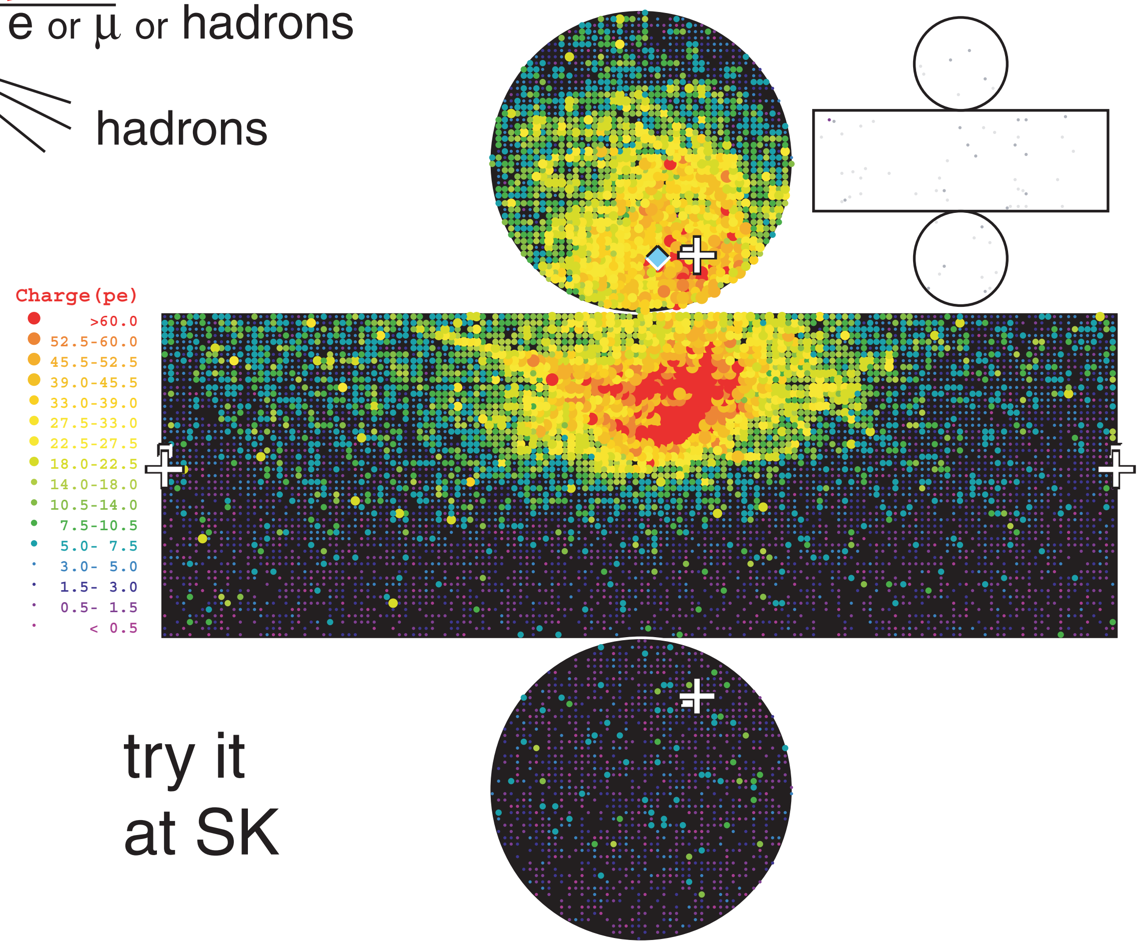


expect ~100 events

events have large visible energy (> 2 GeV)

multiple rings
(not all may be reconstructed)

over threshold,
only upward-going neutrinos
have sufficient oscillation length



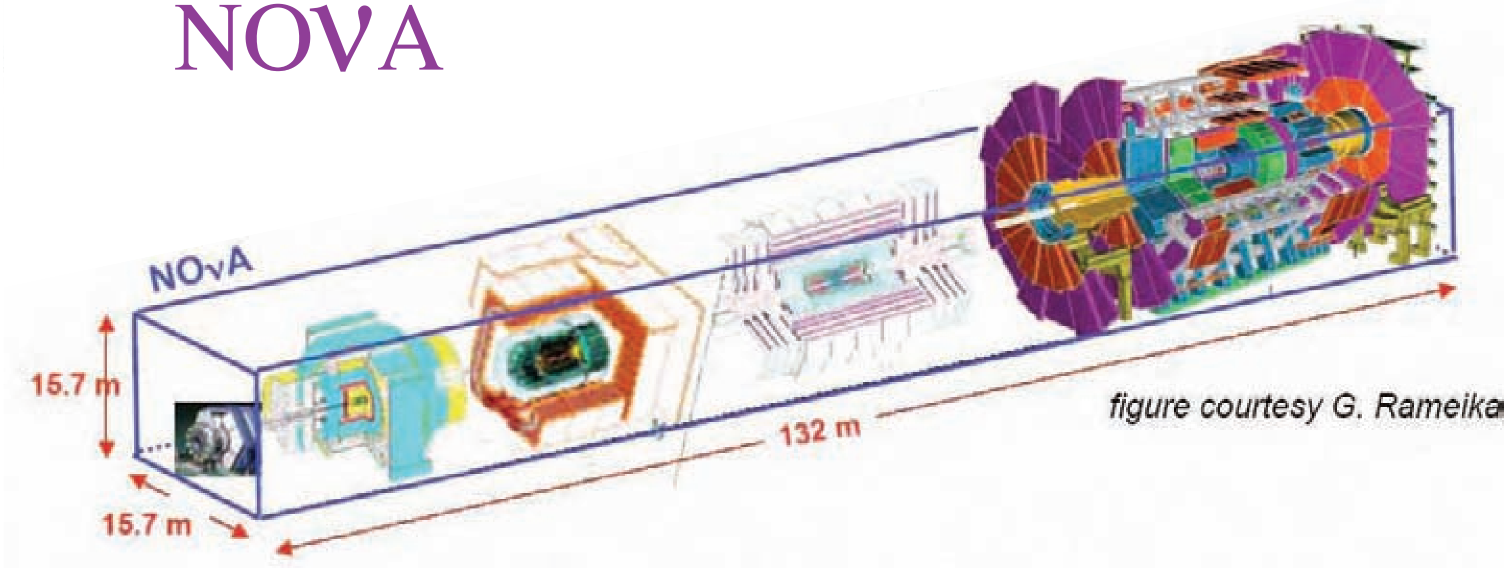
try it
at SK

Tau appearance is special emphasis for CNGS (CERN-Gran Sasso) experiment OPERA
~ only a handful of events events, but with emulsion tracdker to identify kink of tau decay

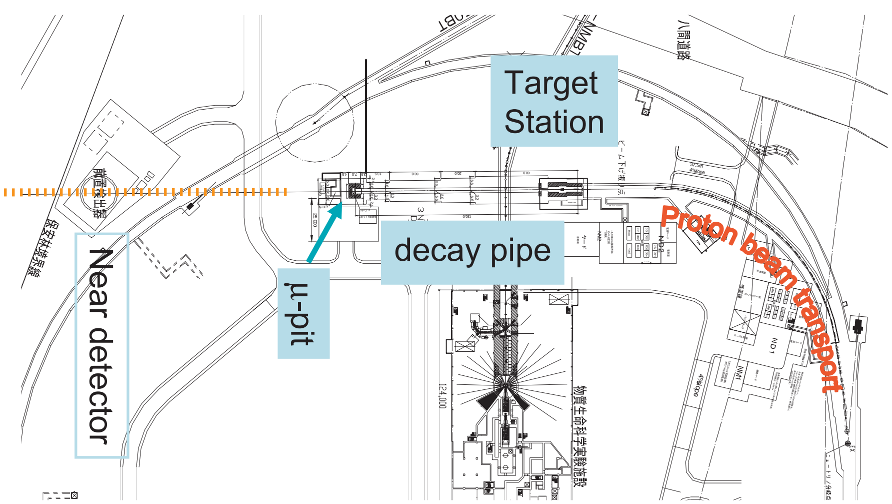
Off-Axis Experiments

Let's build a new detector off-axis from the existing NuMI beam!

NOVA

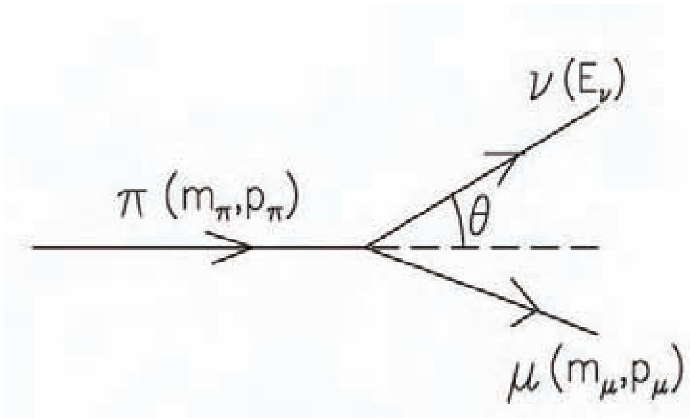


Let's build a new beam off-axis to the existing Super-K detector!



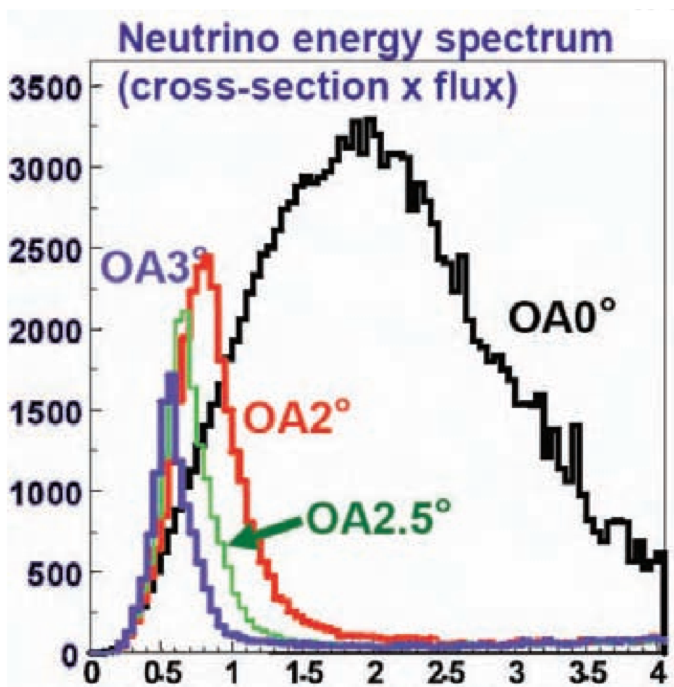
T2K

Off-axis kinematics

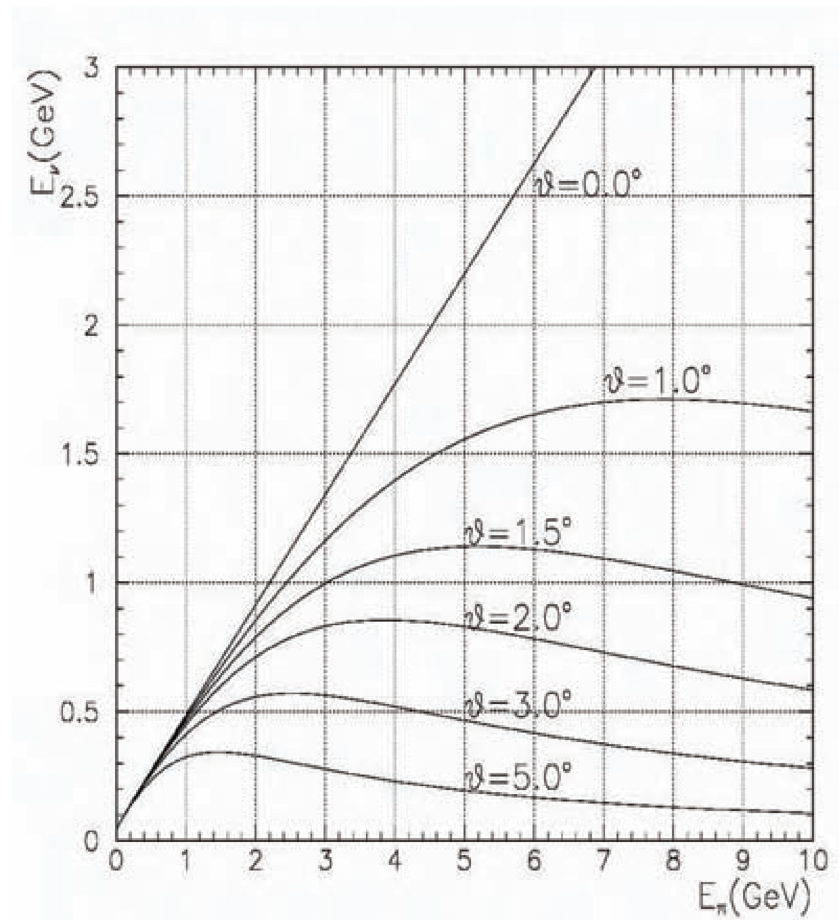


$$E_\nu = \frac{m_\pi^{\ 2} - m_\mu^{\ 2}}{2(E_\pi - p_\pi \cos\theta)}$$

Angle chooses peak energy

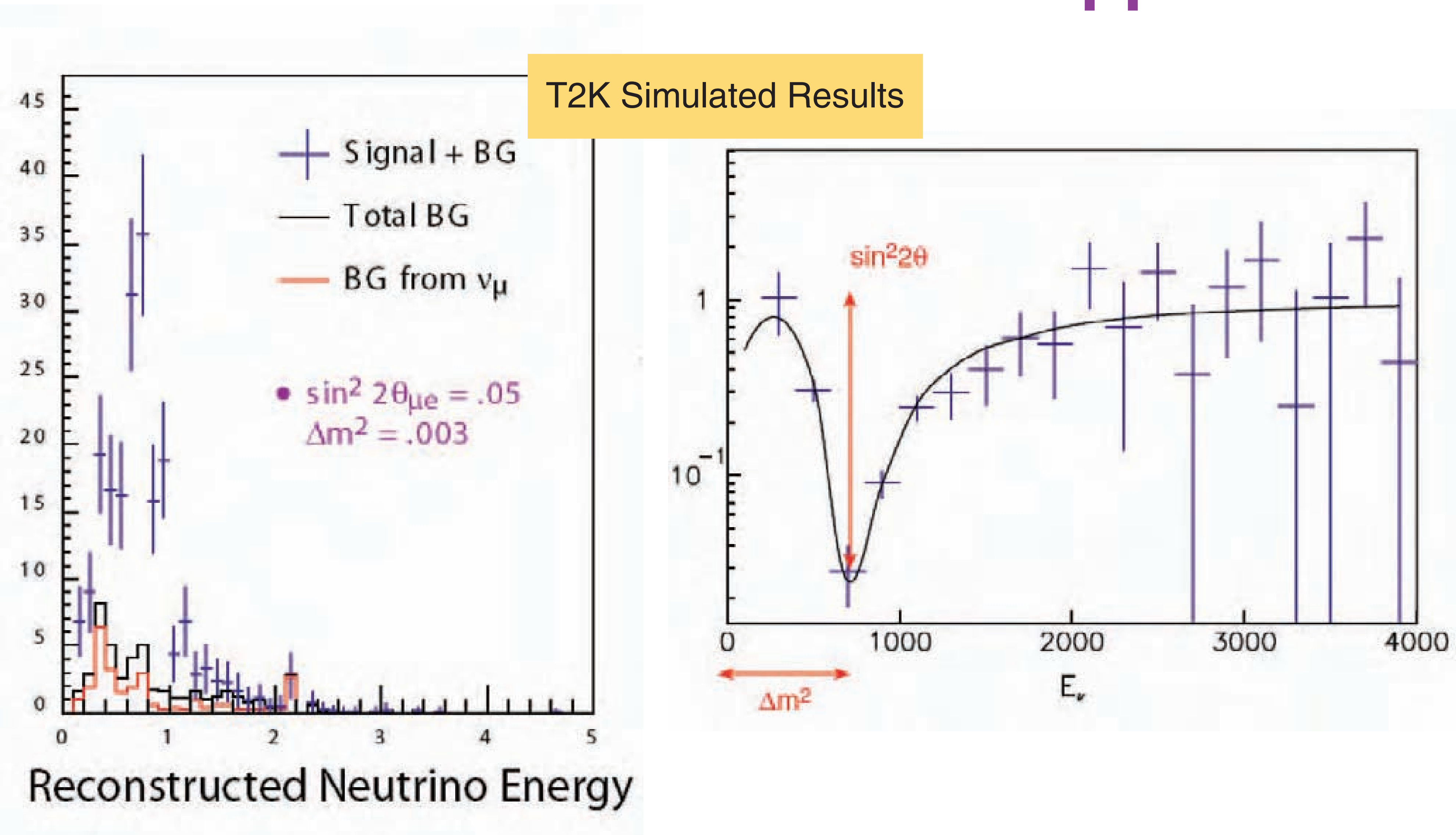


Neutrino Energy (GeV)



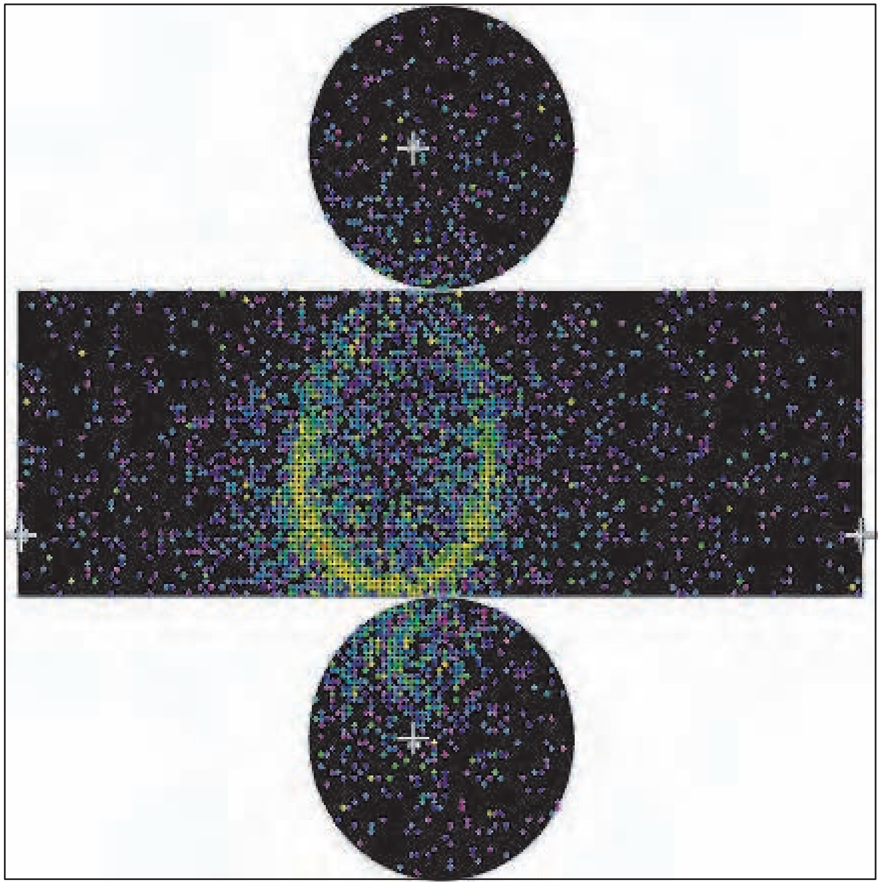
Electron Neutrino Appearance and Muon Neutrino Disappearance

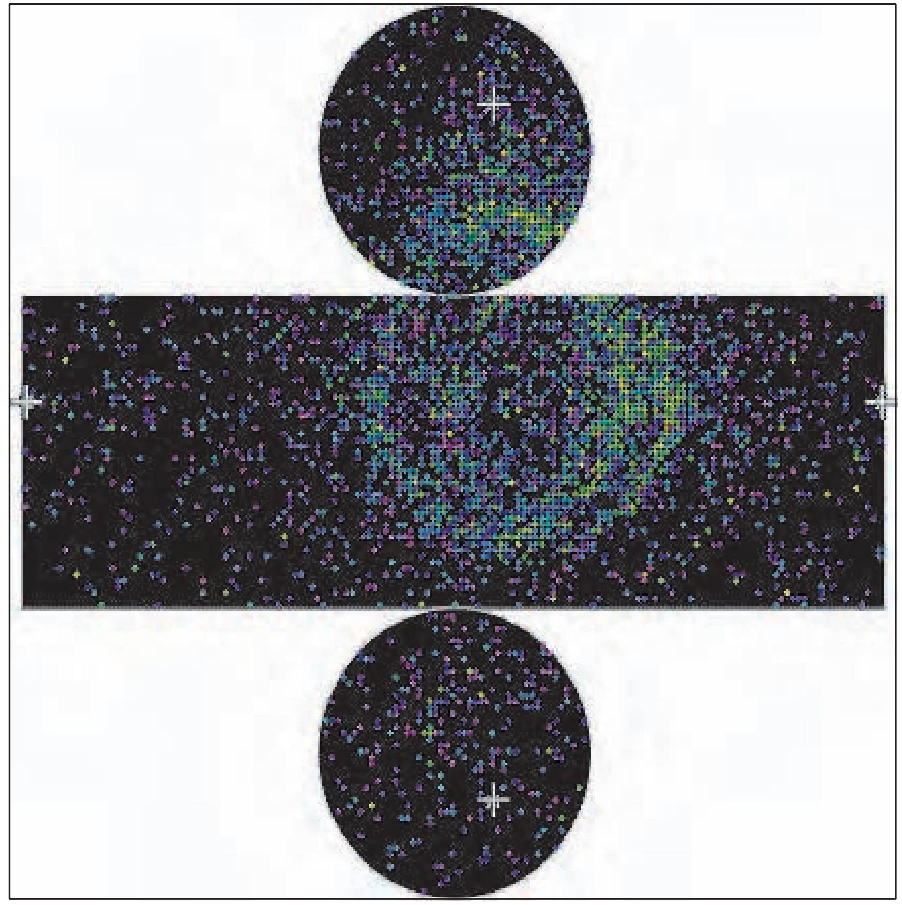
T2K Simulated Results



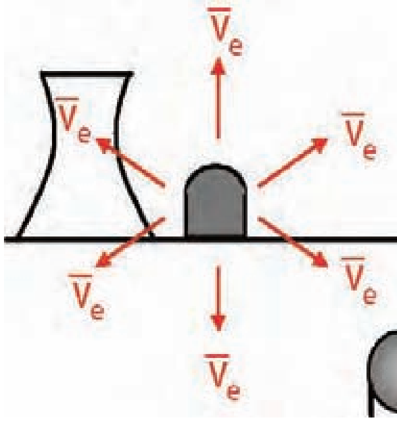
NOνA has comparable goals

Background is Single Pizero Events

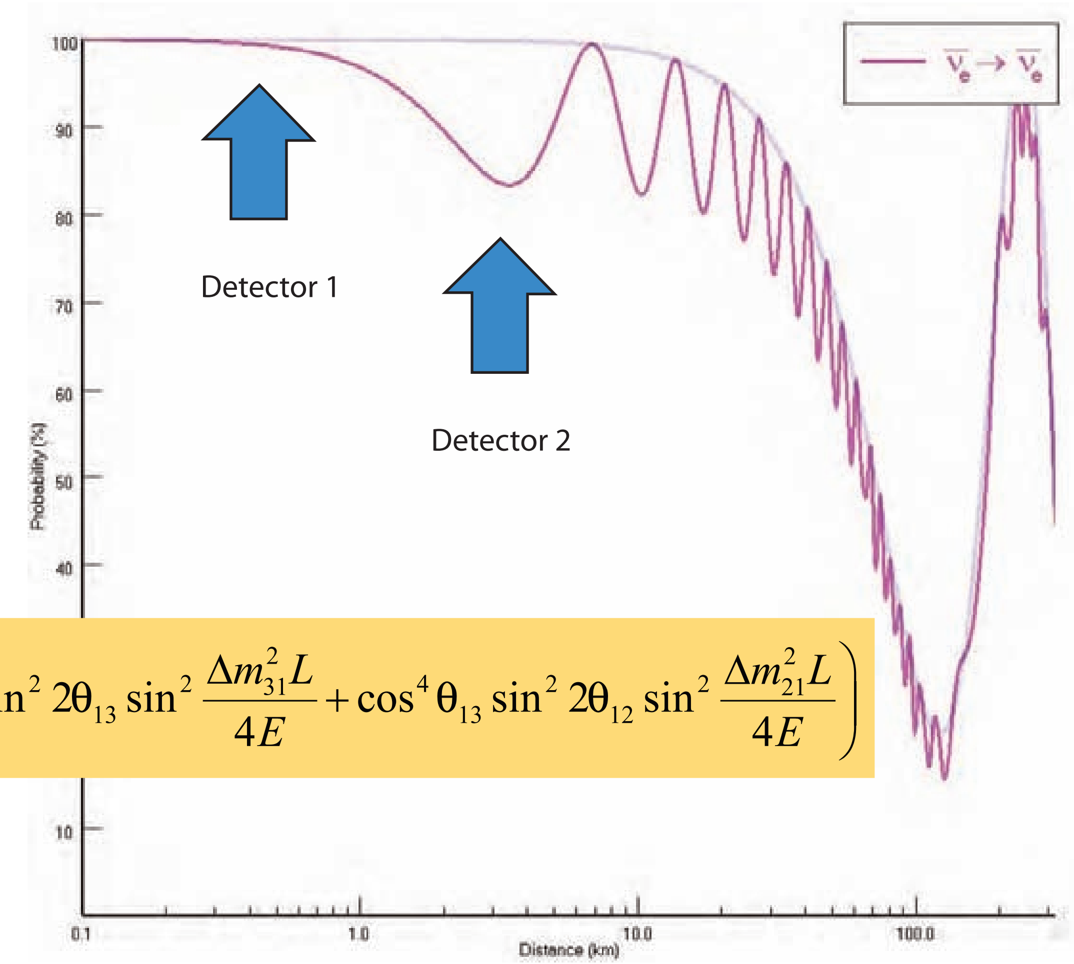




Two Detector Reactor Experiment



requires very careful control of systematic effects



$$P_{ee} \rightarrow 1 - \left(\sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E} \right)$$

Best case scenario:
small wiggles assume θ_{13} as large as allowed by CHOOZ limit

smaller values θ_{13}:
P_{surv} recedes to the faint blue curve

must believably measure small difference in event rates

Several sites being considered:

Braidwood (IL)
Daya Bay (HK)
Chooz (France)

How We Might Know What We Do Not Yet Know

- Are there only three neutrino states? (LSND)
    - mini-BooNE (2005)
- Can we really make an appearance experiment?
    - CNGS, SK? (τ); T2K, NOνA (e)
- What is the absolute mass scale?
    - KATRIN, $0\nu\beta\beta$, precision cosmology?
- Are neutrinos their own antiparticle? (Majorana)
    - Numerous $0\nu\beta\beta$ experiments being proposed
- What is the sign of the large Δm^2? (heirarchy  or )
    - NOνA + T2K
- What is the value of θ_{23}? Is it truly maximal?
    - NOνA, T2K
- What is the value of θ_{13}? Is it really zero?
    - NOνA, T2K, new reactor experiment
- What is the value of δ?
    - upgraded off-axis experiments (eg. Hyper-K+4MW beam)

plus challenging proposed accelerators like β-beams and muon storage rings