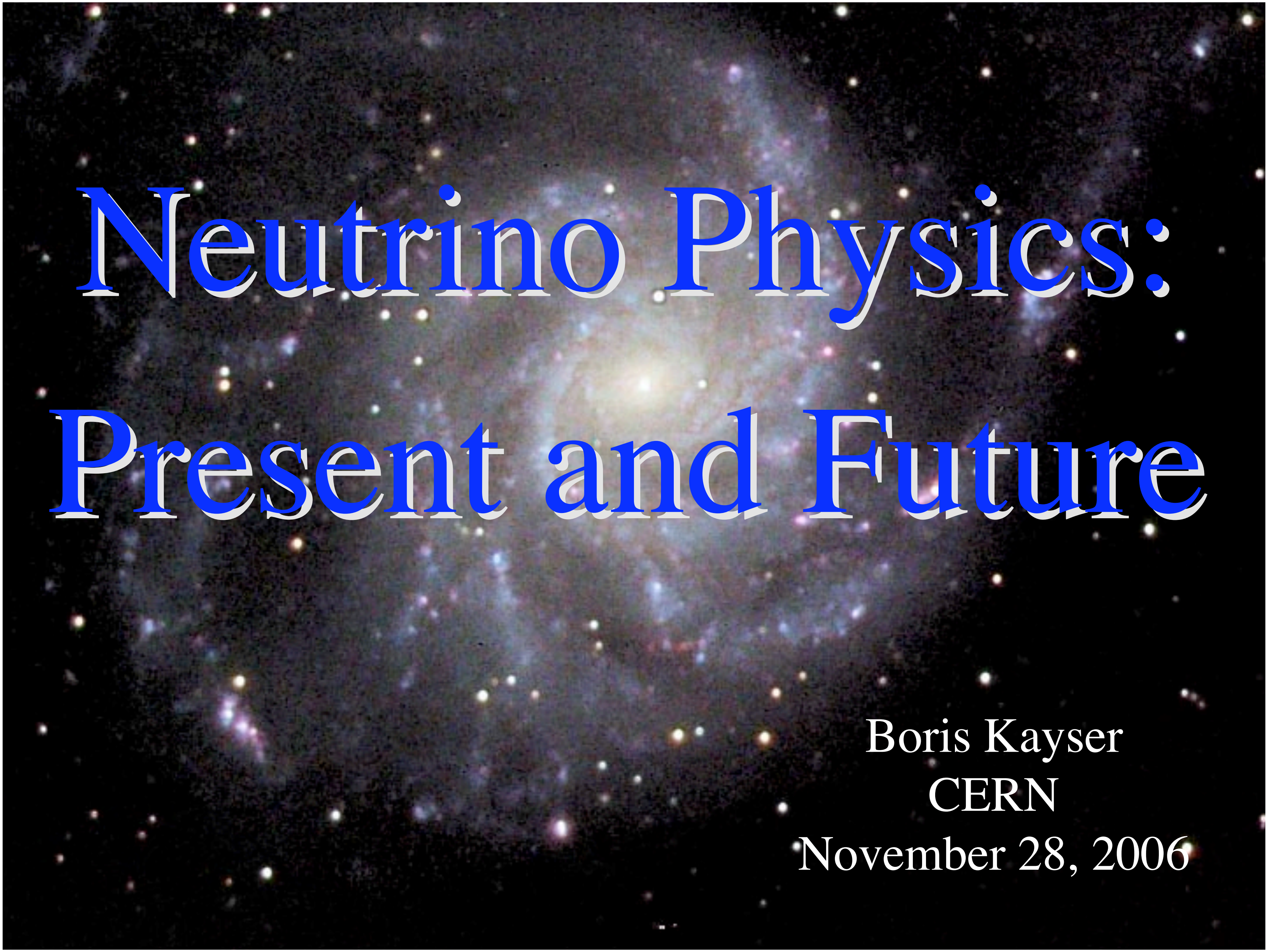

Neutrino Physics: Present and Future

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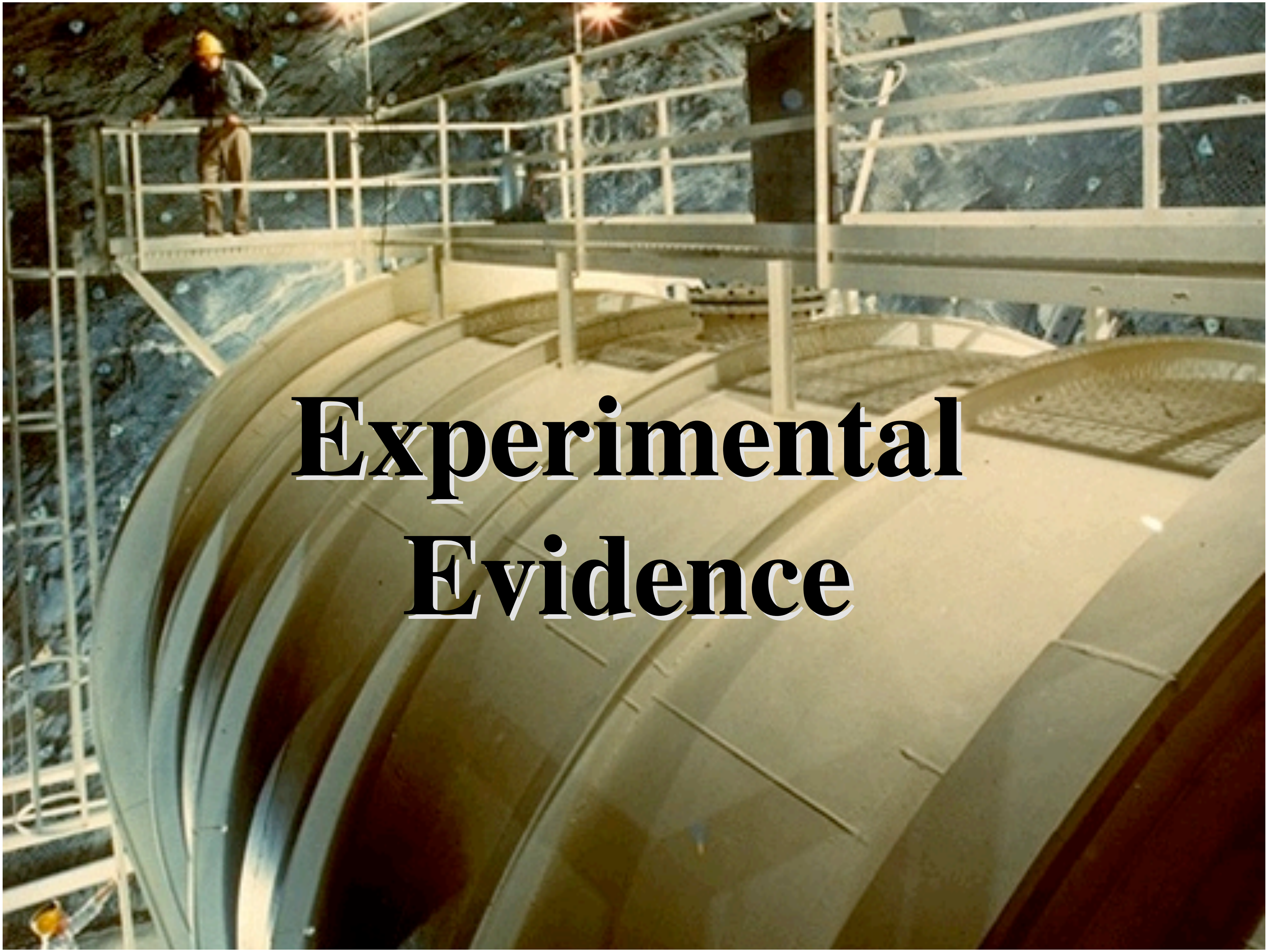
CERN
November 28, 2006

Experimental Evidence



Evidence For Flavor Change

Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor (L ~ 180 km)	Compelling
Atmospheric	Compelling
Accelerator (L = 250 and 735 km)	Compelling
Stopped μ^+ Decay $\left(\begin{matrix}\text{LSND}\\ L \approx 30\text{ m}\end{matrix}\right)$	Unconfirmed

Solar Neutrinos

Nuclear reactions in the core of the sun produce ν_e. Only ν_e.

The Sudbury Neutrino Observatory (SNO) measures, for the high-energy part of the solar neutrino flux:

$$\nu_{sol}\, d \rightarrow e\, p\, p \;\Rightarrow \phi_{\nu_e}$$

$$\nu_{sol}\, d \rightarrow \nu\, n\, p \;\Rightarrow \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$$

From the two reactions,

$$\frac{\phi_{\nu_e}}{\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}} = 0.340 \pm 0.023\ (\text{stat}) \pm 0.030\ (\text{syst})$$

Clearly, $\phi_{\nu_\mu} + \phi_{\nu_\tau} \neq 0$. Neutrinos change flavor.

The now-established mechanism for solar $\nu_e \rightarrow \nu_\mu / \nu_\tau$ is not oscillation in vacuum but the —

Large Mixing Angle version of the —

Mikheyev Smirnov Wolfenstein

— Effect.

This occurs as the neutrinos stream outward through solar material. It involves interactions with matter, but also requires neutrino mass and mixing.

How Does the Large Mixing Angle MSW Effect Work?

The solar *matter effect* is important for the high-energy ^{8}B neutrinos, not the low-energy pp neutrinos.

Since ν_3 couples at most feebly to electrons (to be discussed), and solar neutrinos are born ν_e, the solar neutrinos are mixtures of just ν_1 and ν_2.

Solar neutrino flavor change is $\nu_e \rightarrow \nu_x$, where ν_x is some combination of ν_μ and ν_τ.

This is a 2-neutrino system.

In the sun,

$$H = \frac{\Delta m^2_{sol}}{4E}\begin{bmatrix} -\cos 2\theta_{sol} & \sin 2\theta_{sol} \\ \sin 2\theta_{sol} & \cos 2\theta_{sol} \end{bmatrix} + \sqrt{2}G_F N_e \begin{array}{c} \begin{array}{cc} \nu_e & \nu_x \end{array} \\ \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \end{array} \begin{array}{c} \\ \nu_e \\ \nu_x \end{array}$$

At the center of the sun,

$$\sqrt{2}\, G_F N_e \approx 0.75 \times 10^{-5}\ \mathrm{eV}^2 / \mathrm{MeV}\ .$$

For $\Delta m^2_{sol} \approx 8 \times 10^{-5}$ eV^2 and typical ^{8}B neutrino energy of ~ 8 MeV,

$$\Delta m^2_{sol} / 4E \approx 0.25 \times 10^{-5}\ \mathrm{eV}^2 / \mathrm{MeV}\ .$$

The interaction term in H dominates, and ν_e is approximately an eigenstate of H.*

*For the (E ~ 0.2MeV) pp neutrinos, H_{Vac} dominates.

The ^{8}B solar neutrino propagates outward adiabatically.

It remains the slowly - changing heavier eigenstate of the slowly - changing H.

It emerges from the sun as the heavier eigenstate of H_{Vac}, ν_2.*

It stays ν_2 until it reaches the earth. Nothing “oscillates”!

Since $\nu_2 = \nu_e \sin\theta_{sol} + \nu_x \cos\theta_{sol}$, (See 2 × 2 U matrix)

Prob[See ν_e at earth] $= \sin^2\theta_{sol}$.

*Good to 91% (Nunokawa, Parke, Zukanovich-Funchal)

Reactor (Anti)Neutrinos

The vacuum neutrino properties Δm^2_{sol} and θ_{sol} implied by LMA-MSW are —

$$\Delta m^2_{sol} \sim 8 \text{ x } 10^{-5}\, \mathrm{eV}^2 \; ; \; \theta_{sol} \sim 34^{o} \, .$$

This has implications for the behavior of reactor $\overline{\nu}_e$.

The fractional importance of matter effects on an oscillation involving a vacuum splitting Δm^2 is —

$$\overbrace{[(G_{\text{Fermi}}/\sqrt{2})\underset{\substack{\uparrow\\ \text{Density of electrons}}}{N_e}]}^{\text{Interaction energy}} \;/\; \overbrace{[\Delta m^2/4E]}^{\text{Vacuum energy}} \equiv x\ .$$

For $\Delta m^2 = \Delta m^2_{\text{sol}} \sim 8 \times 10^{-5}\ \text{eV}^2$,

$$x = 2.5 \times 10^{-3}\ E(\text{MeV})\ .$$

At reactor energies of a few MeV,

this is negligible.

The KamLAND detector is ~ 180 km from reactor $\overline{\nu}_e$ sources.

For KamLAND, at say 3 MeV, the argument of —

$$\sin^2[1.27\Delta m^2_{sol}(eV^2)L(km)/E(GeV)]$$

is —

$$3.9 \text{ x } (\pi/2).$$

The experiment sees an energy-averaged oscillation.

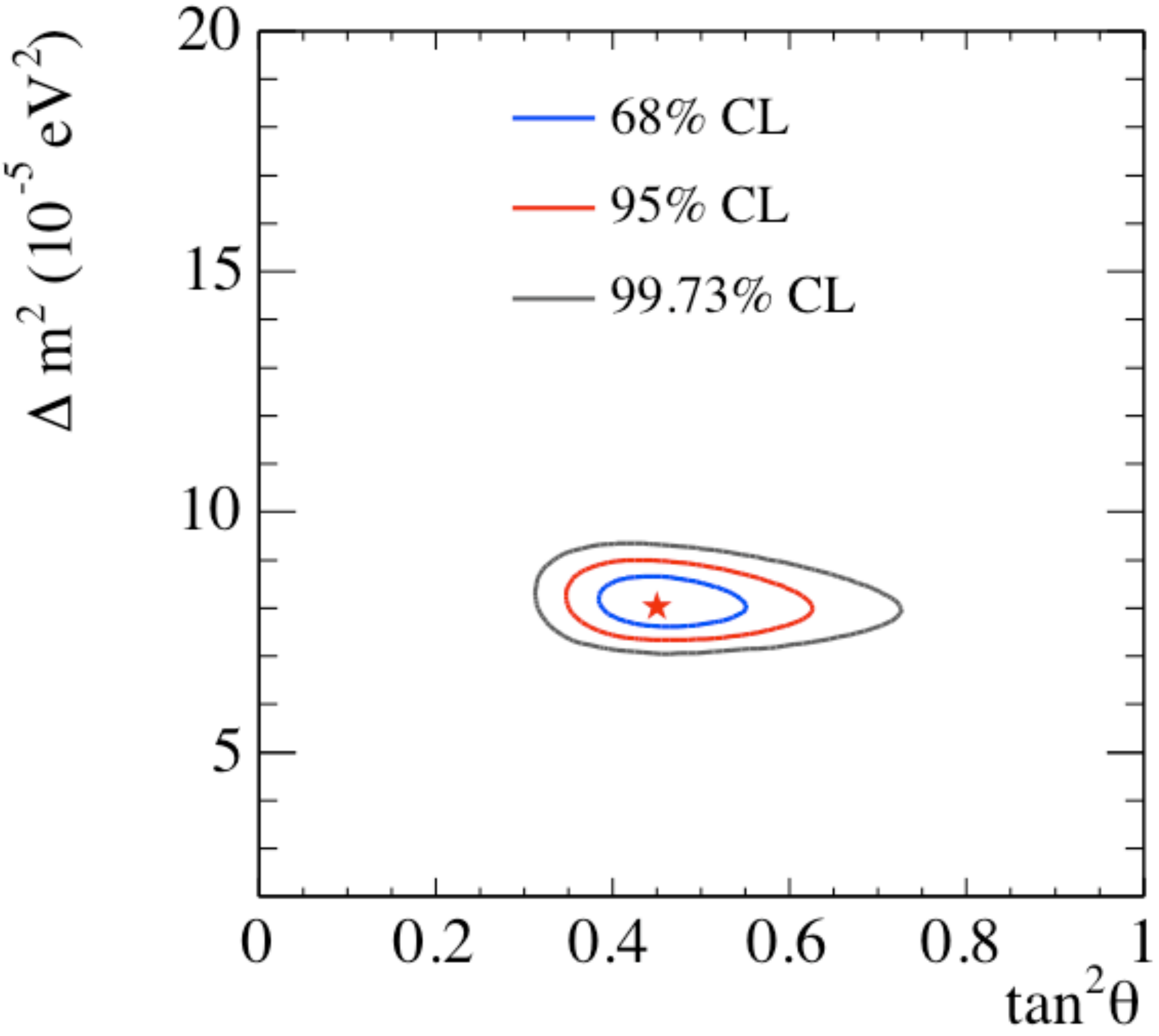
It should see substantial disappearance of $\overline{\nu}_e$ flux.

KamLAND actually does see —

$$\frac{\phi_{\overline{\nu}_e}}{\phi_{\overline{\nu}_e}\Big|_{\text{No Disappearance}}} = 0.658 \pm 0.044(\text{stat}) \pm 0.047(\text{syst})\ .$$

Reactor $\overline{\nu}_e$ do disappear.

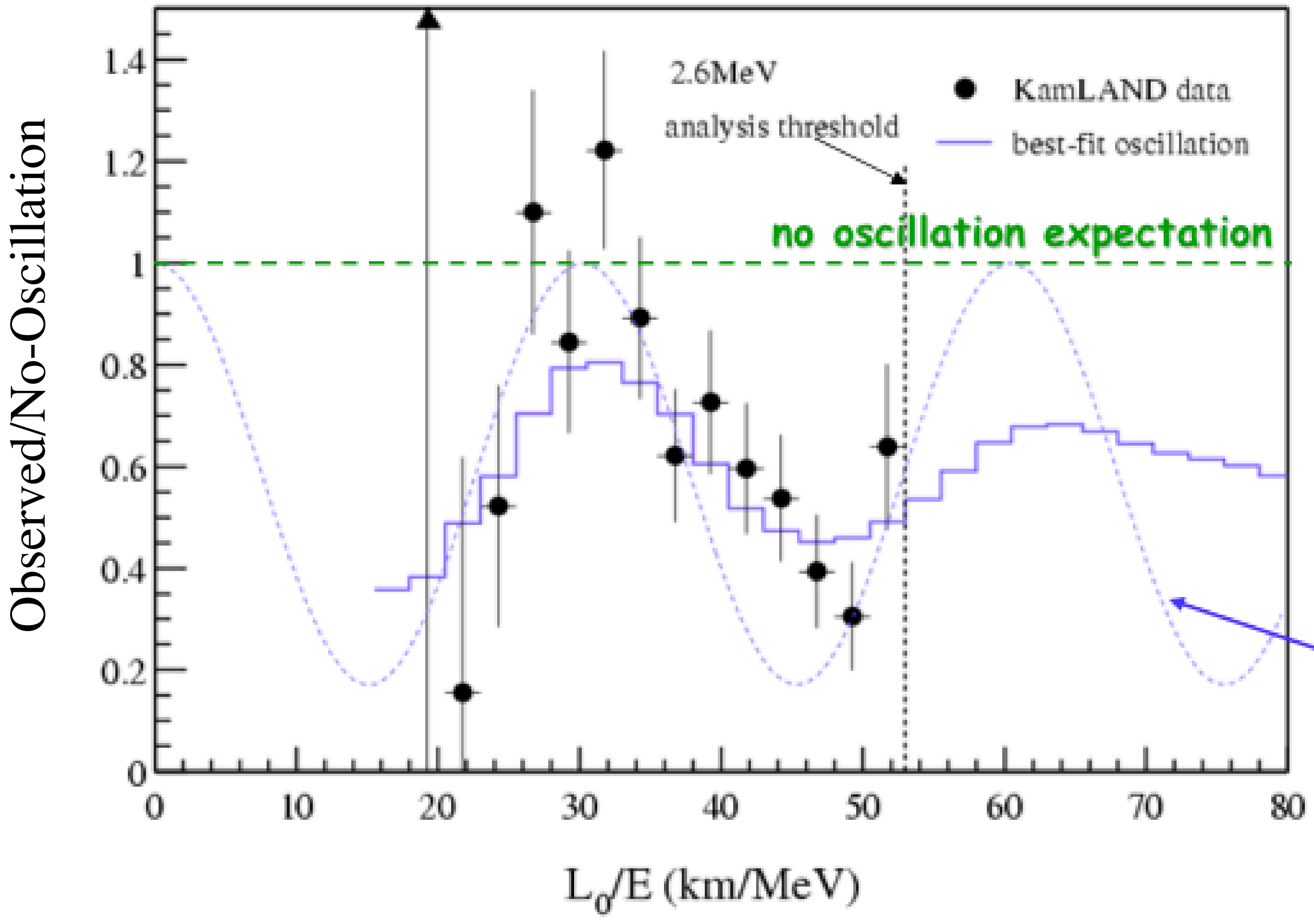
Flavor change, with Δm^2_{sol} and θ_{sol} in the LMA-MSW range, fits both the solar and reactor data.



From
nucl-ex/
0502021

Solar Δm^2 and mixing angle from SNO analysis of solar neutrino and KamLAND data

Evidence for the oscillation of flavor change

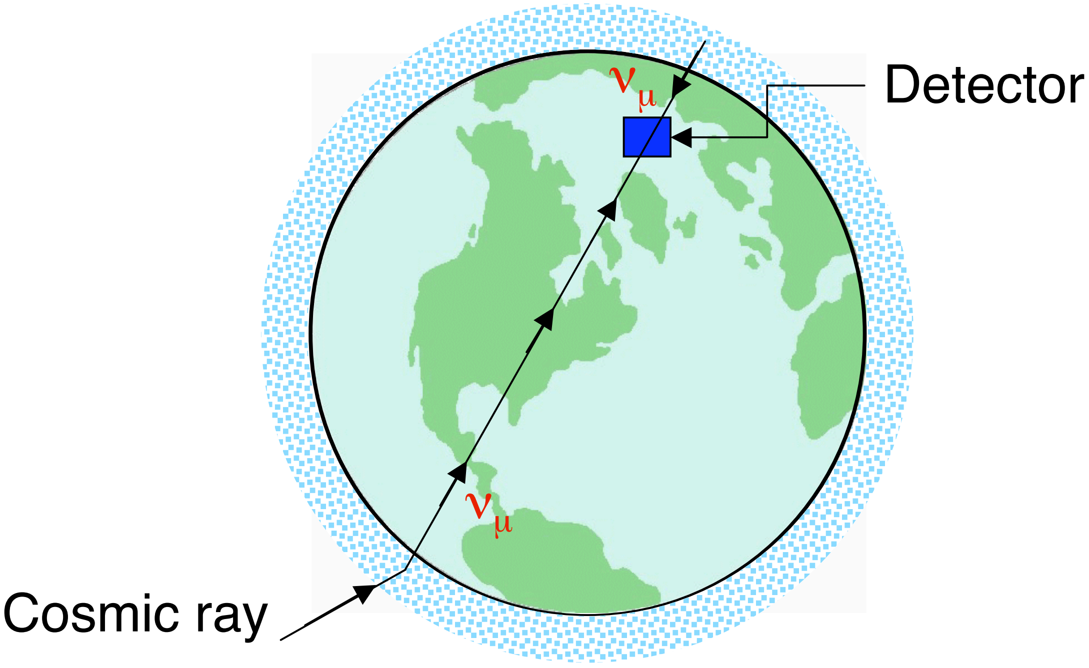


From G. Gratta
at Neutrino 04

Hypothetical single 180km baseline experiment

KamLAND $\bar{\nu}_e$ event rate vs. L/E, assuming each $\bar{\nu}_e$ traveled $L = L_0 = 180$ km.

Atmospheric Neutrinos



Isotropy of the $\gtrsim$ 2 GeV cosmic rays + Gauss' Law + No ν_μ disappearance

$$\Longrightarrow \quad \frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 1 \, .$$

But Super-Kamiokande finds for $E_\nu > 1.3$ GeV

$$\frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 0.54 \pm 0.04 \, .$$

Half of the upward-going, long-distance-traveling ν_μ are disappearing.

Voluminous atmospheric neutrino data are well described by —

$$\nu_\mu \longrightarrow \nu_\tau$$

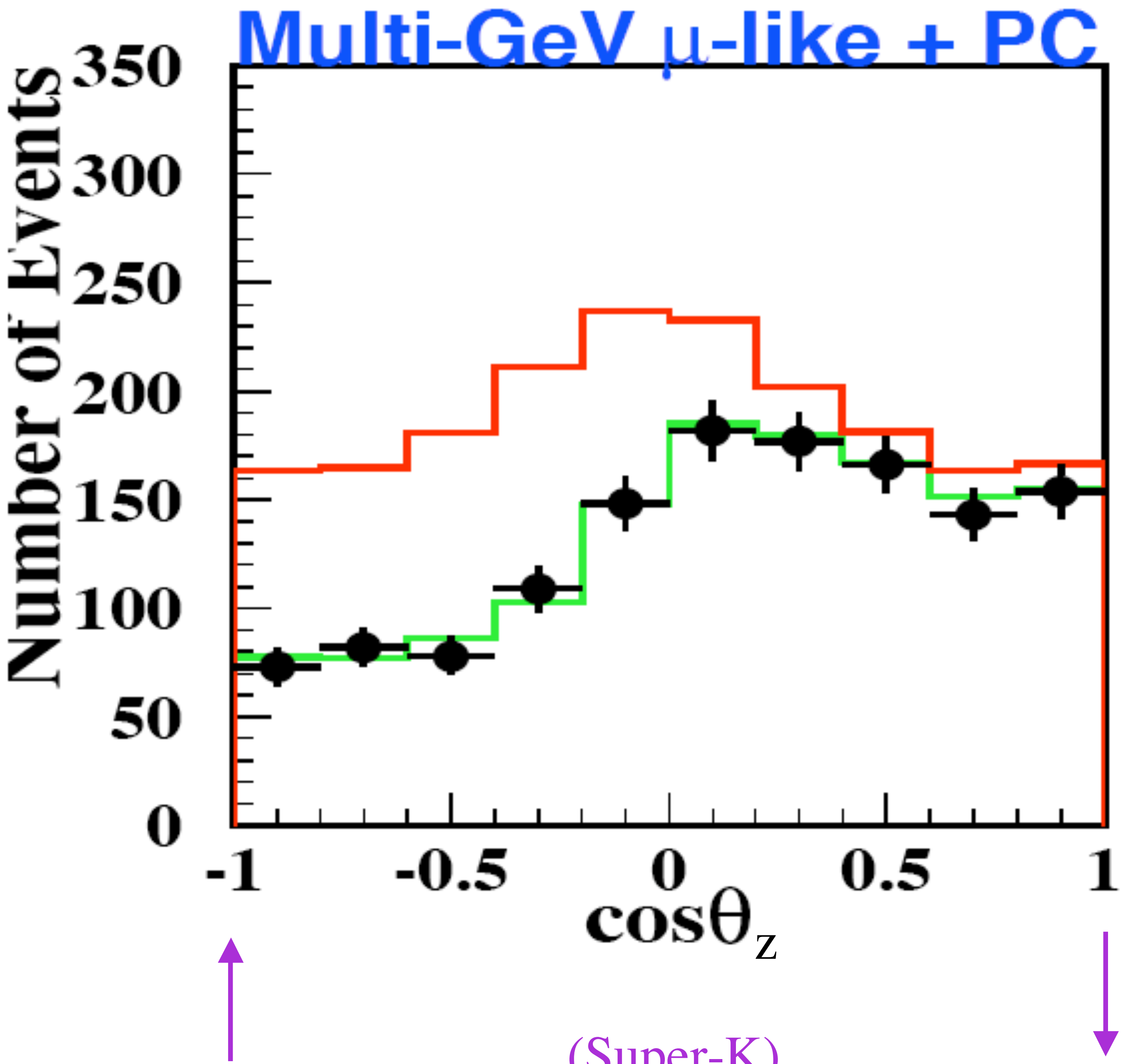
with —

$$1.9 \times 10^{-3} < \Delta m^2_{\mathrm{atm}} < 2.9 \times 10^{-3}\ \mathrm{eV}^2$$

and —

$$\sin^2 2\theta_{\mathrm{atm}} > 0.92$$

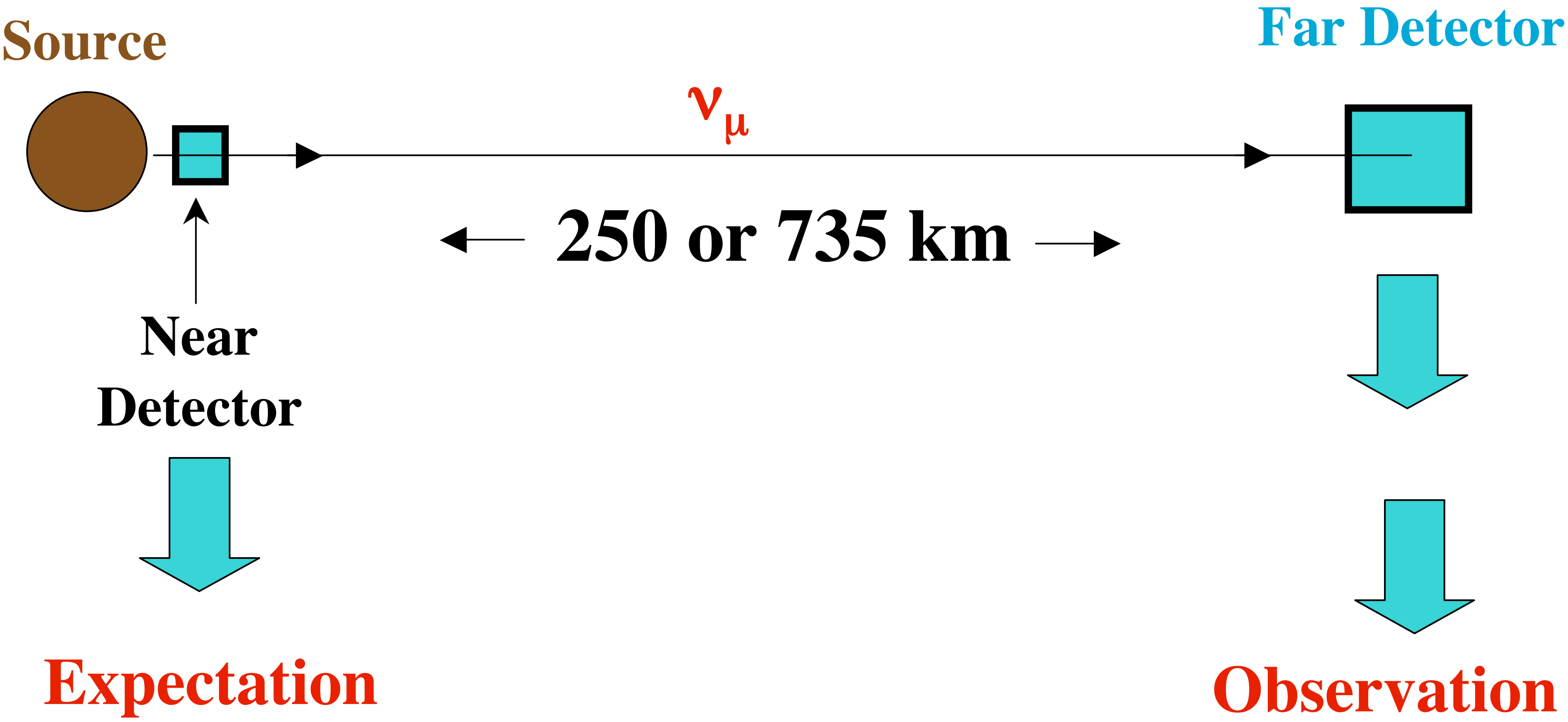
(Super-K 90%CL)


Multi-GeV μ-like + PC
Number of Events
350
300
250
200
150
100
50
0
-1
-0.5
0
0.5
1
cosθz

(Super-K)

Accelerator Neutrinos

Two experiments: K2K and MINOS



Source

Far Detector

ν_μ

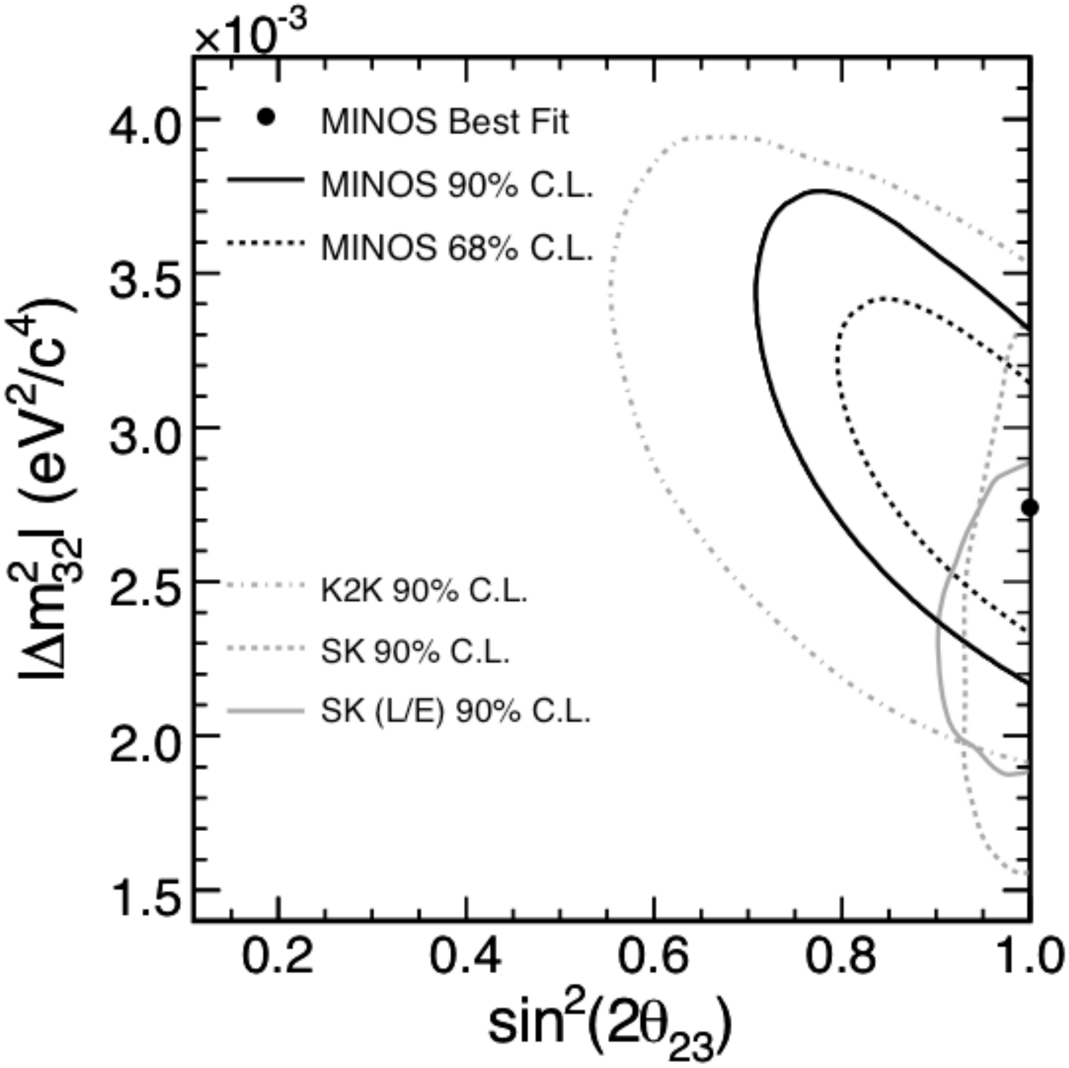
← 250 or 735 km →

Near Detector

Expectation

Observation

Latest Results From MINOS



From
hep-ex/
0607088

The Atmospheric Δm^2 and Mixing Angle

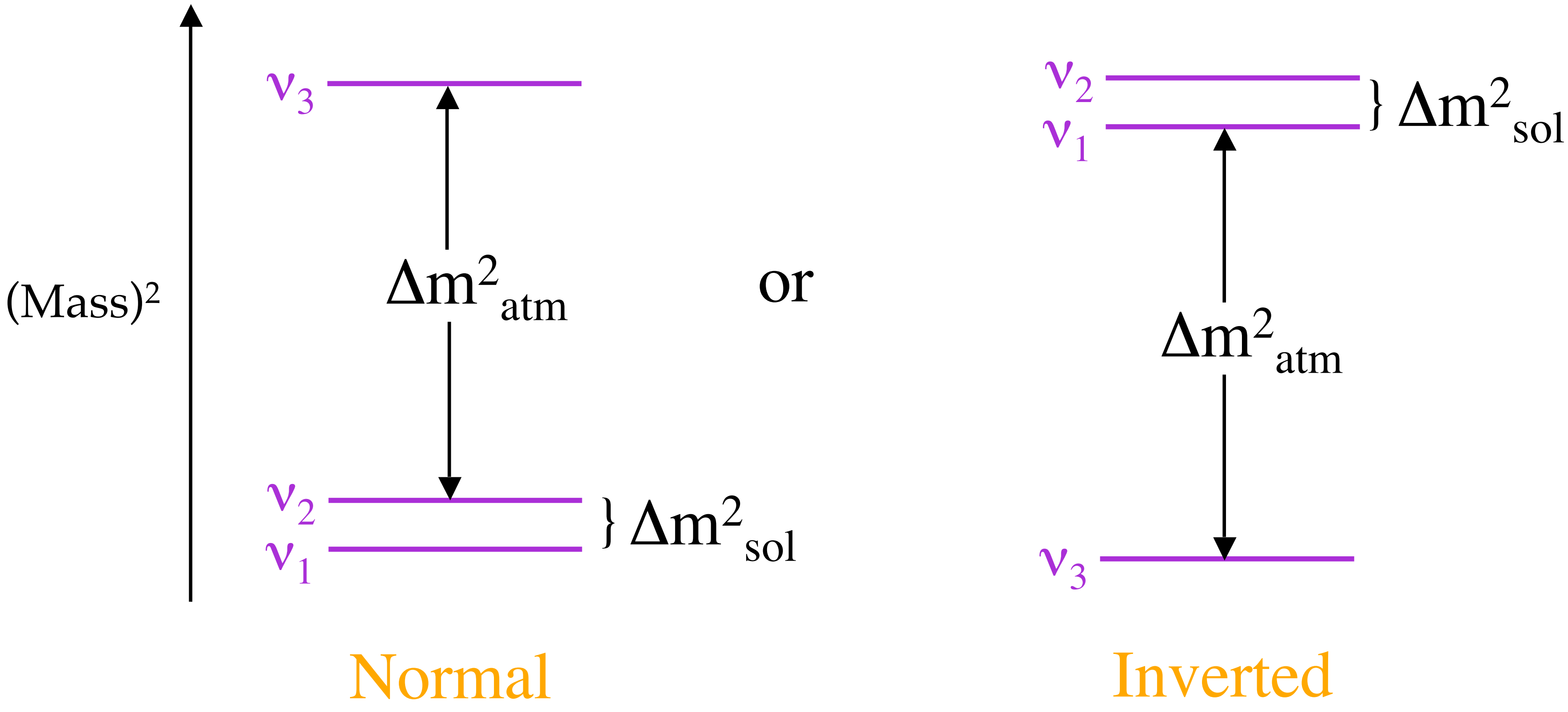
Coming: A Test of the $\nu_\mu \rightarrow \nu_\tau$ Hypothesis

Look for τ production in Gran Sasso by neutrinos born as ν_μ at CERN.

(CNGS)

What We Have Learned

The (Mass)^2 Spectrum



$\Delta m^2_{sol} \cong 8 \times 10^{-5}\ \mathrm{eV}^2$, $\Delta m^2_{atm} \cong 2.7 \times 10^{-3}\ \mathrm{eV}^2$

Are there *more* mass eigenstates, as LSND suggests?

Leptonic Mixing

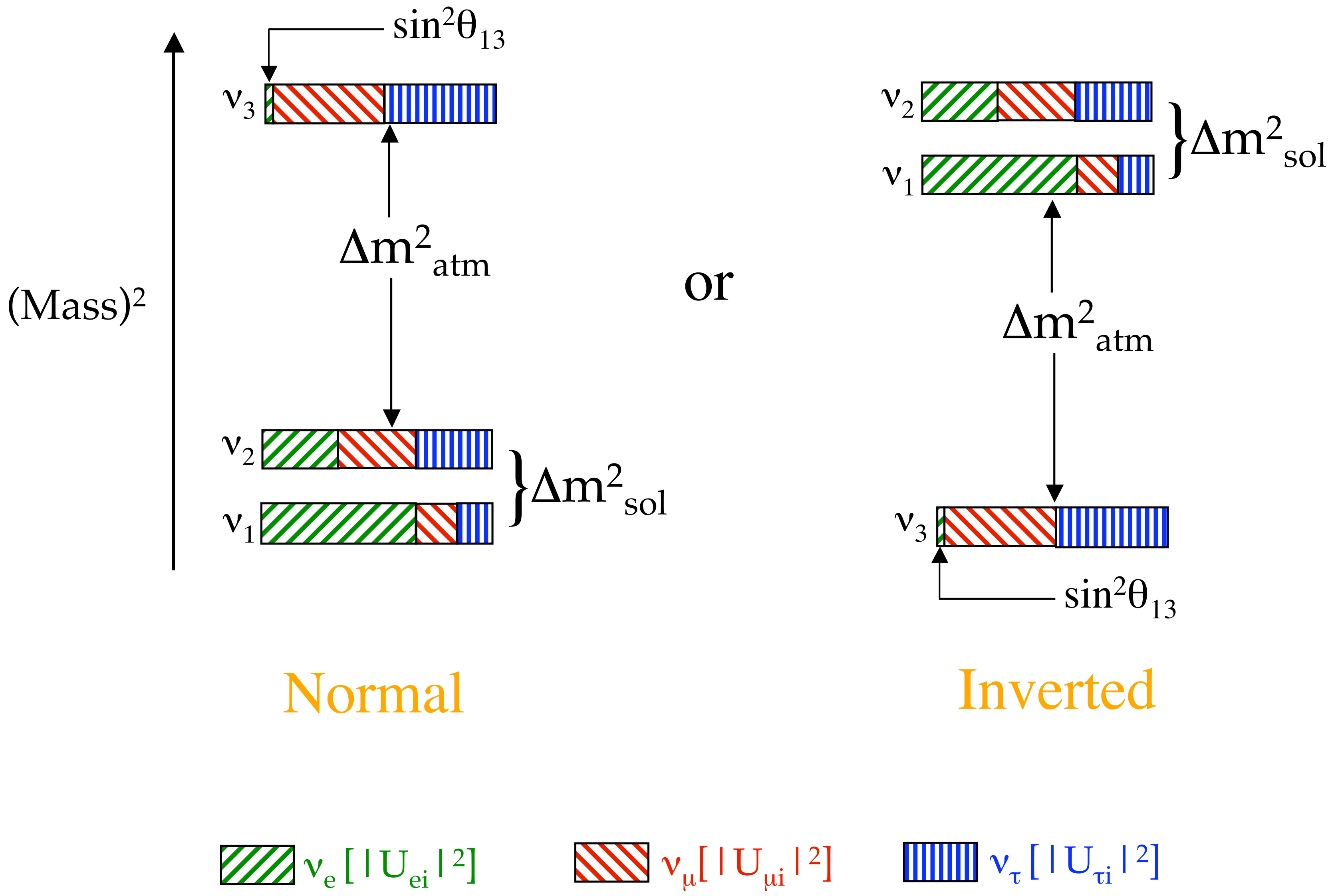
This has the consequence that —

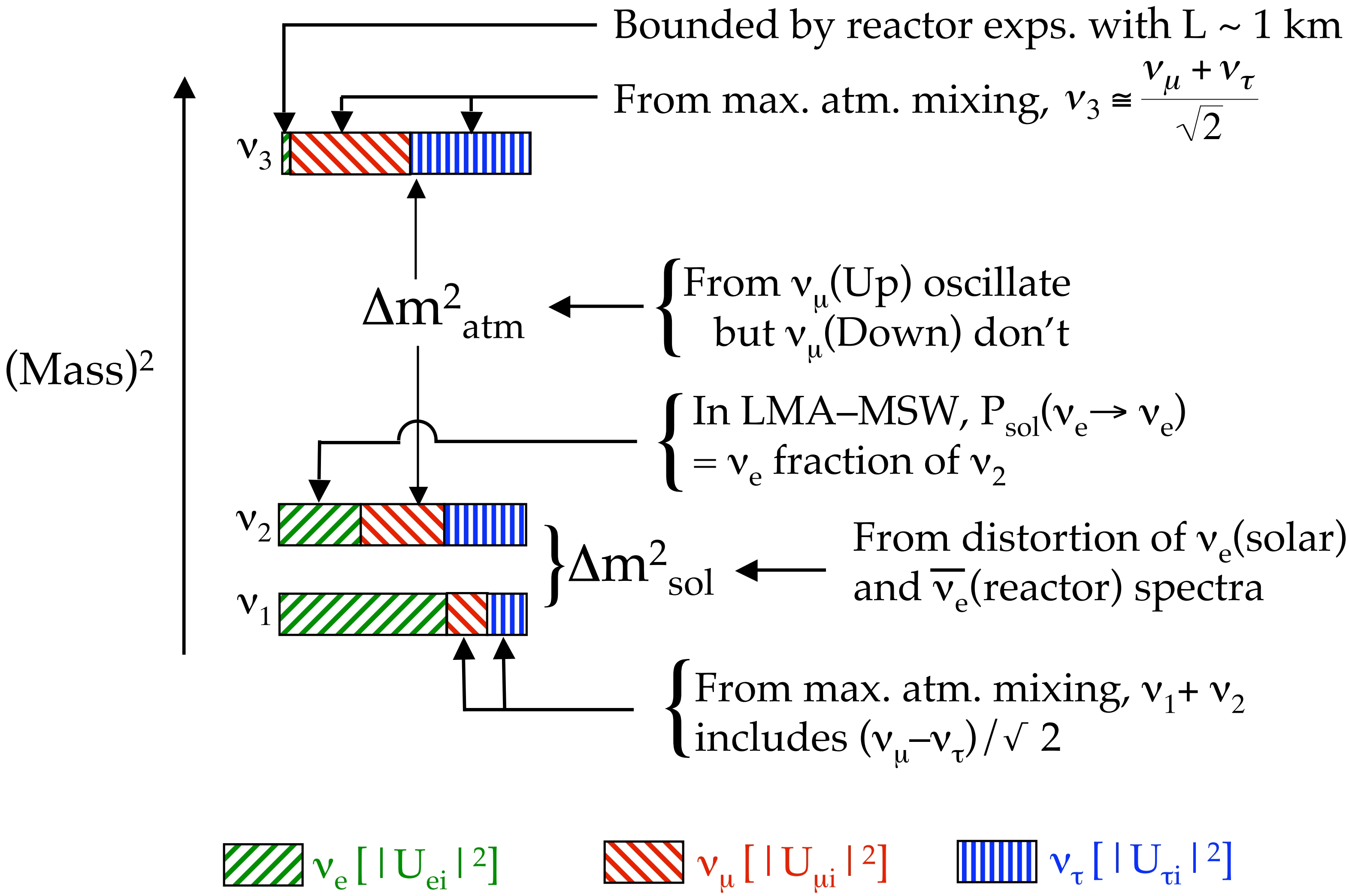
$$|\nu_i> = \sum_\alpha U_{\alpha i} \, |\nu_\alpha> .$$

Flavor-α fraction of $\nu_i = |U_{\alpha i}|^2$.

When a ν_i interacts and produces a charged lepton, the probability that this charged lepton will be of flavor α is $|U_{\alpha i}|^2$.

The spectrum, showing its approximate flavor content, is





Bounded by reactor exps. with L ~ 1 km

From max. atm. mixing, $\nu_3 \cong \frac{\nu_\mu + \nu_\tau}{\sqrt{2}}$

ν_3

Δm^2_{atm}

From ν_μ(Up) oscillate but ν_μ(Down) don't

(Mass)^2

In LMA–MSW, $P_{sol}(\nu_e \rightarrow \nu_e)$ = ν_e fraction of ν_2

ν_2

ν_1

Δm^2_{sol}

From distortion of ν_e(solar) and $\overline{\nu_e}$(reactor) spectra

From max. atm. mixing, $\nu_1 + \nu_2$ includes $(\nu_\mu - \nu_\tau)/\sqrt{2}$

▨ ν_e [$|U_{ei}|^2$] ▨ ν_μ [$|U_{\mu i}|^2$] ▥ ν_τ [$|U_{\tau i}|^2$]

The Mixing Matrix

$$U = \overset{\text{Atmospheric}}{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}} \times \overset{\text{Cross-Mixing}}{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}} \times \overset{\text{Solar}}{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

$$c_{ij} \equiv \cos\theta_{ij}$$
$$s_{ij} \equiv \sin\theta_{ij}$$

$$\times \underset{\text{Majorana } \cancel{CP} \text{ phases}}{\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

$\theta_{12} \approx \theta_{sol} \approx 34°$, $\theta_{23} \approx \theta_{atm} \approx 37\text{-}53°$, $\theta_{13} \lesssim 10°$

δ would lead to $P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$. $\cancel{CP}$

But note the crucial role of $s_{13} \equiv \sin\theta_{13}$.

Good Luck

Because $(\Delta m^2_{sol} / \Delta m^2_{atm}) << 1$ and $\theta_{13} << 1$,
all confirmed flavor change processes seen so far
are effectively two-neutrino processes.

Because $\theta_{13} << 1$, $\theta_{atm} \approx \theta_{23}$ and $\theta_{sol} \approx \theta_{12}$.

This has greatly simplified the analysis
of what is happening.

The Majorana $\not{CP}$ Phases

The phase α_i is associated with
neutrino mass eigenstate ν_i:

$U_{\alpha i} = U^0_{\alpha i} \exp(i\alpha_i/2)$ for all flavors α.

$$\mathrm{Amp}(\nu_\alpha \rightarrow \nu_\beta) = \sum_i U_{\alpha i}^* \exp(-\, i m_i^2 L/2E)\, U_{\beta i}$$

is insensitive to the Majorana phases α_i.

Only the phase δ can cause CP violation in
neutrino oscillation.

There Is Nothing Special About θ_{13}

All mixing angles must be nonzero for $\cancel{CP}$.

For example —

$$P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right) - P\left(\nu_\mu \rightarrow \nu_e\right) = 2\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta$$
$$\times \sin\left(\Delta m^2{}_{31}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{32}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{21}\frac{L}{4E}\right)$$

In the factored form of U, one can put
δ next to θ_{12} instead of θ_{13}.