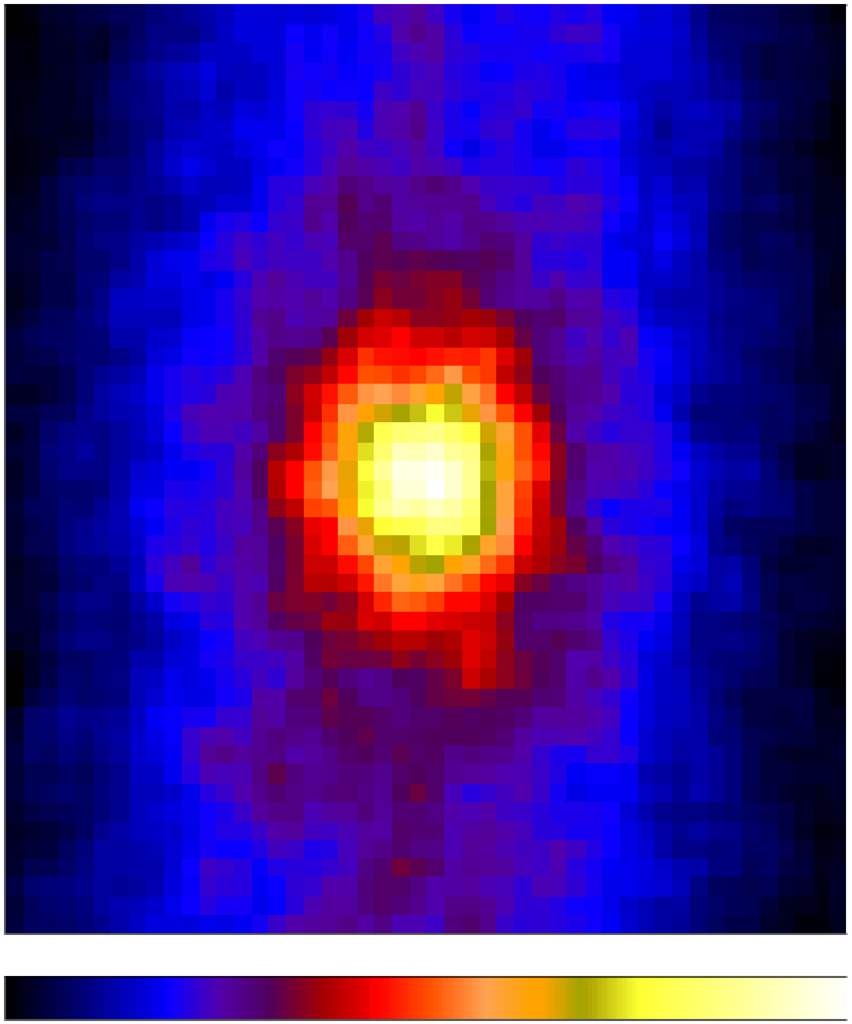
Lecture 3

The neutrino oscillation industry

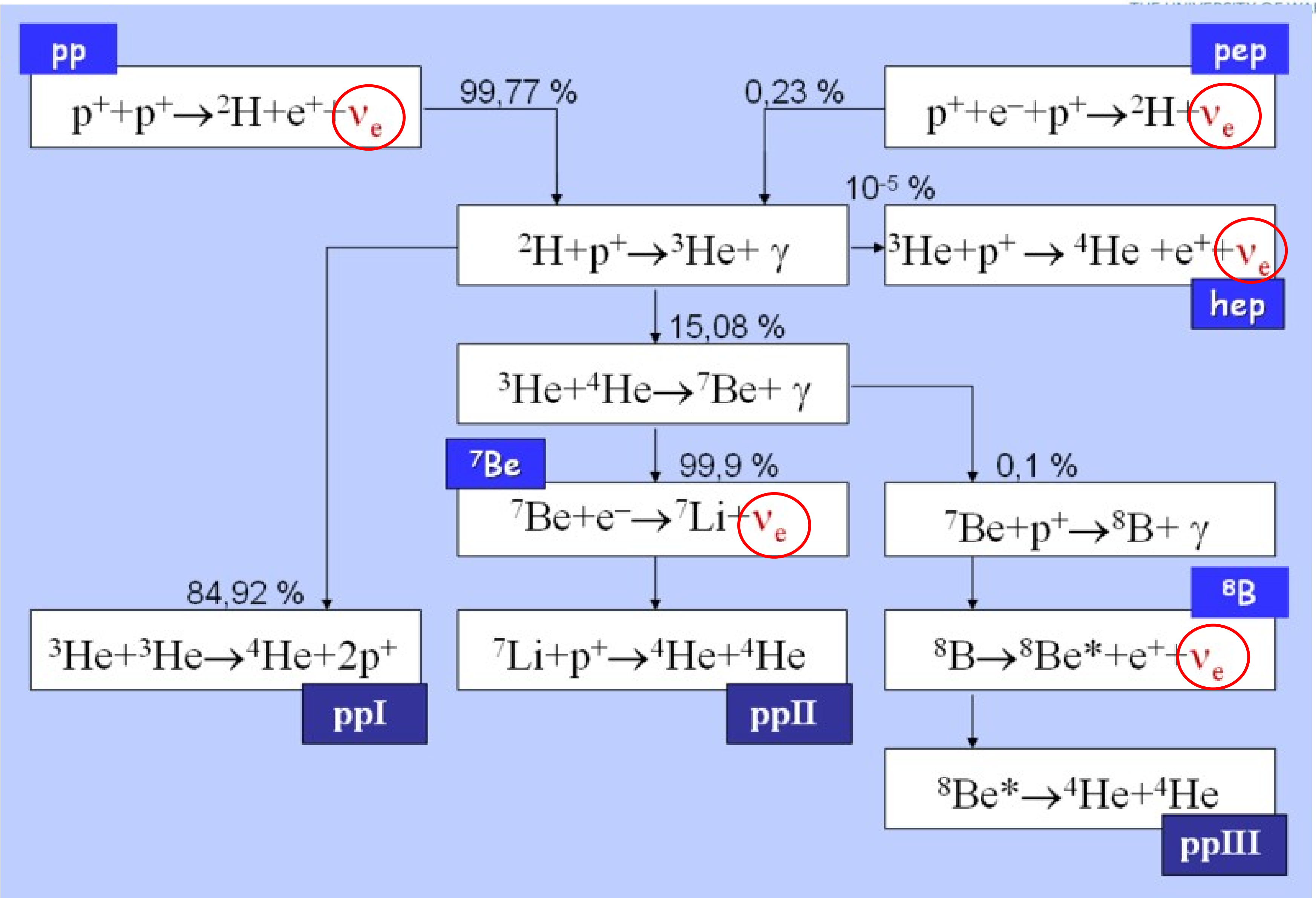
Solar Neutrinos

SuperK : Solar neutrino-gram

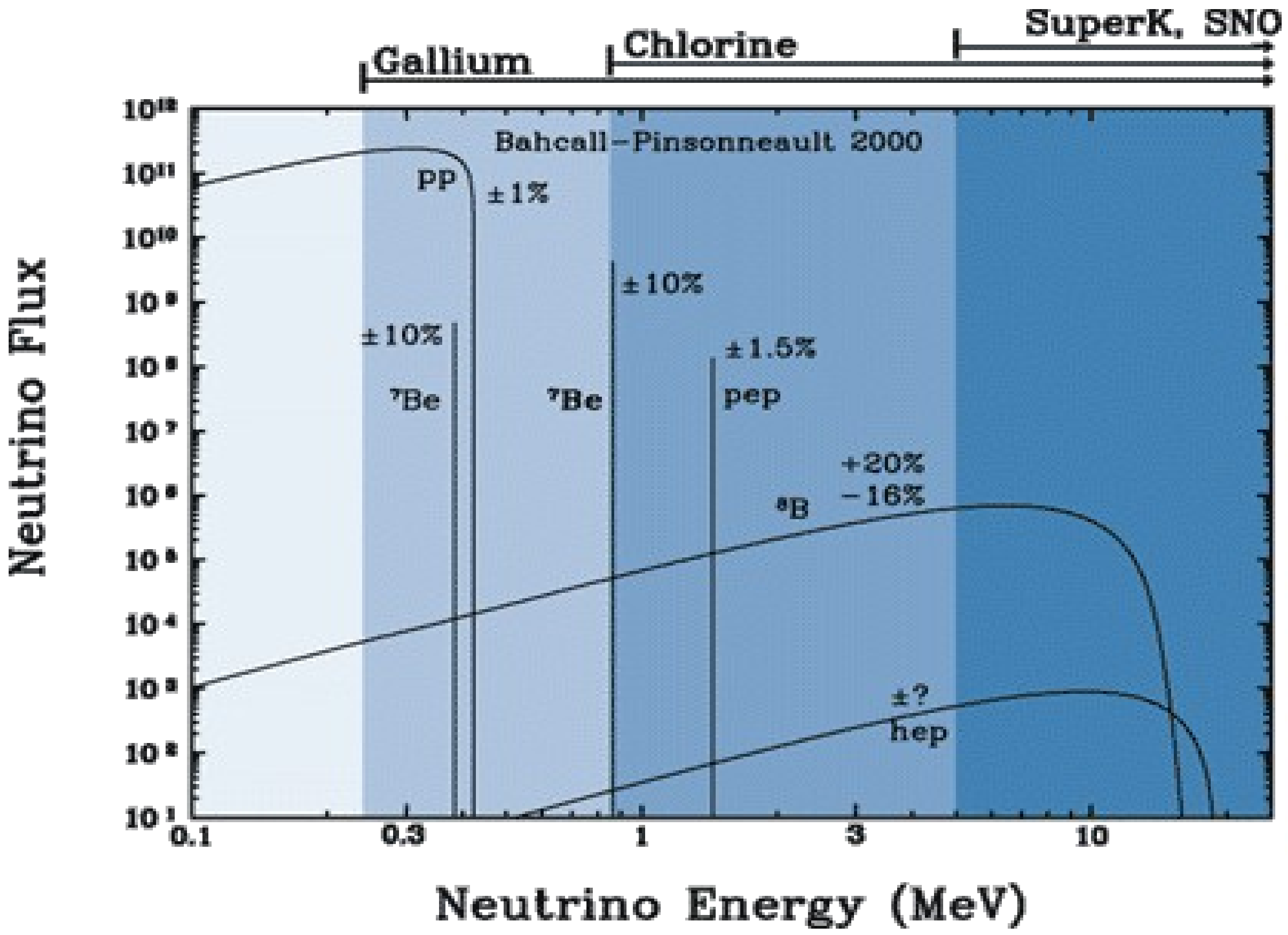


- Light from the solar core takes a million years to reach the surface
- Fusion processes generate electron neutrinos which take 2s to leave
- Solar neutrinos are a direct probe of the solar core
- Roughly 4.0 x 10^{10} solar ν_e per cm^2 per second on earth

Solar neutrino – pp Cycle



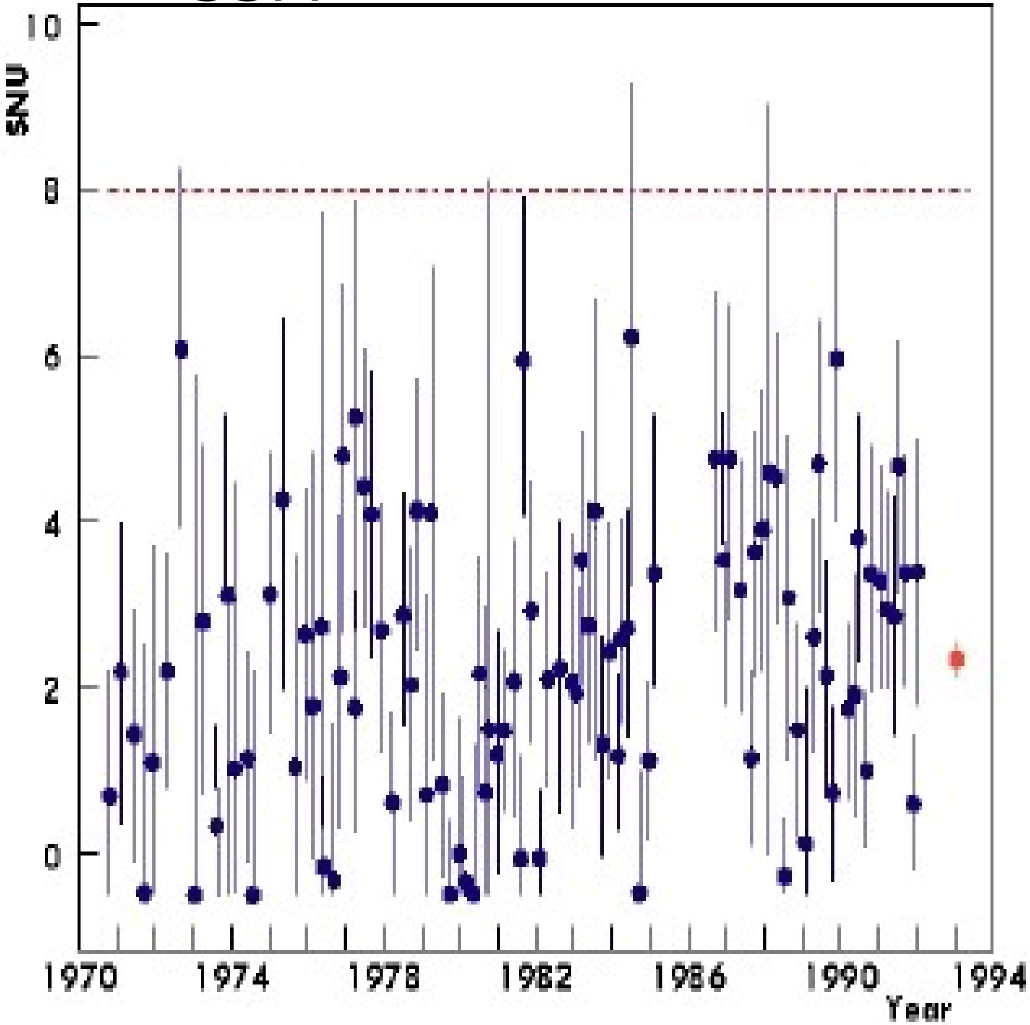
Solar Neutrino Flux



As predicted by Bahcall's Solar model

The Solar Neutrino Problem - Homestake

SSM



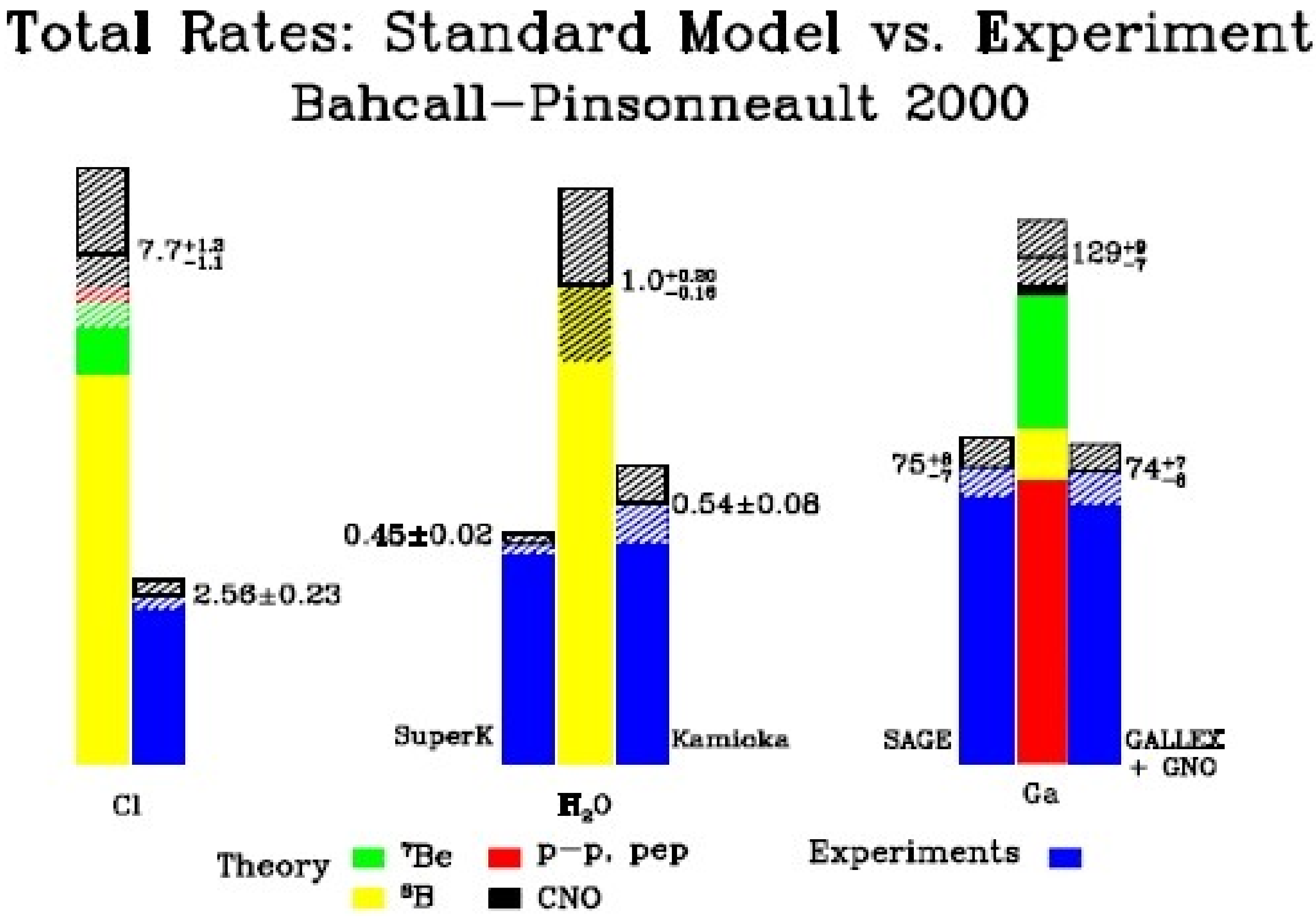
Homestake sensitive to ^{8}B and ^{7}Be *electron neutrinos*

E_{ν} > 800 keV

Observe 1/3 of the expected number of solar neutrinos

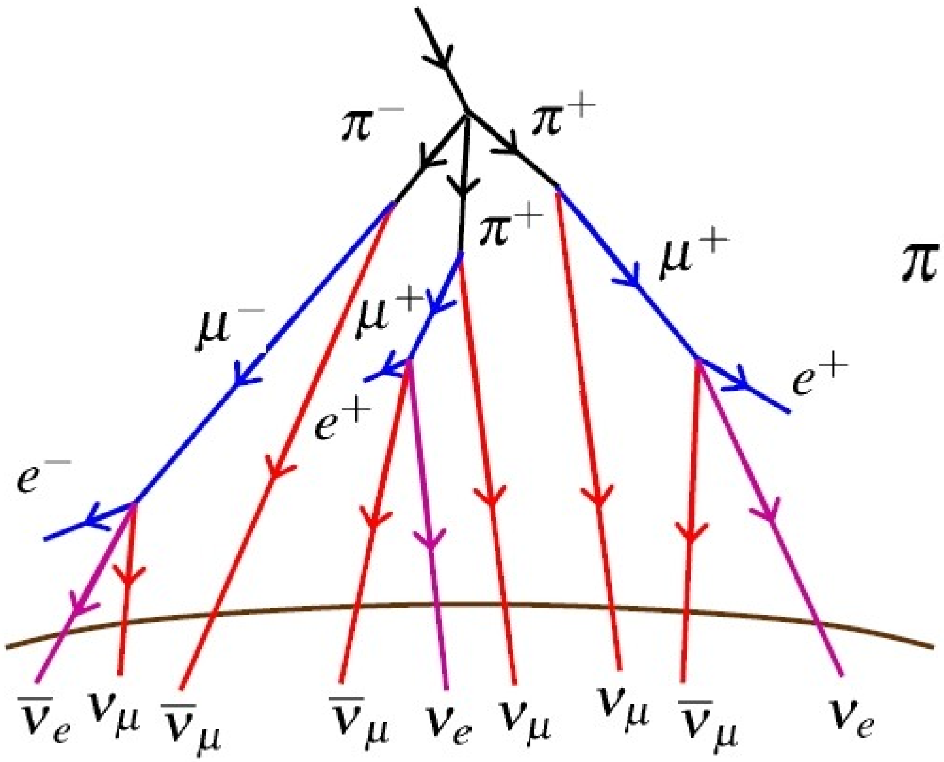
1 SNU = 1 interaction per 10^{36} atoms per second

Experimental summary



Atmospheric neutrinos

High energy cosmic rays interact in the upper atmosphere producing showers of mesons (mostly pions)



Neutrinos produced by

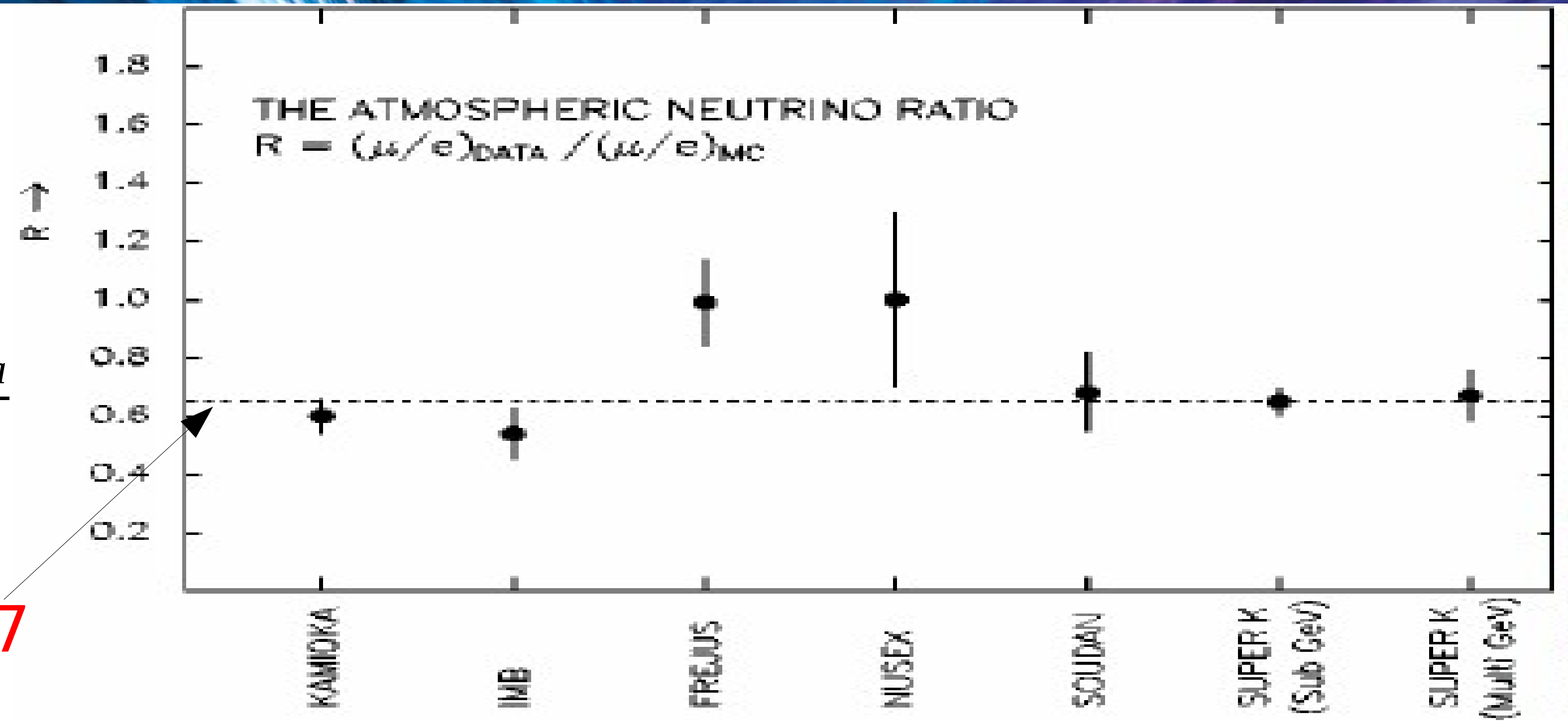
$$\pi^+ \rightarrow \mu^+ \nu_\mu \quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu \qquad\qquad \pi^- \rightarrow \mu^- \bar{\nu}_\mu \quad \hookrightarrow e^- \bar{\nu}_e \nu_\mu$$

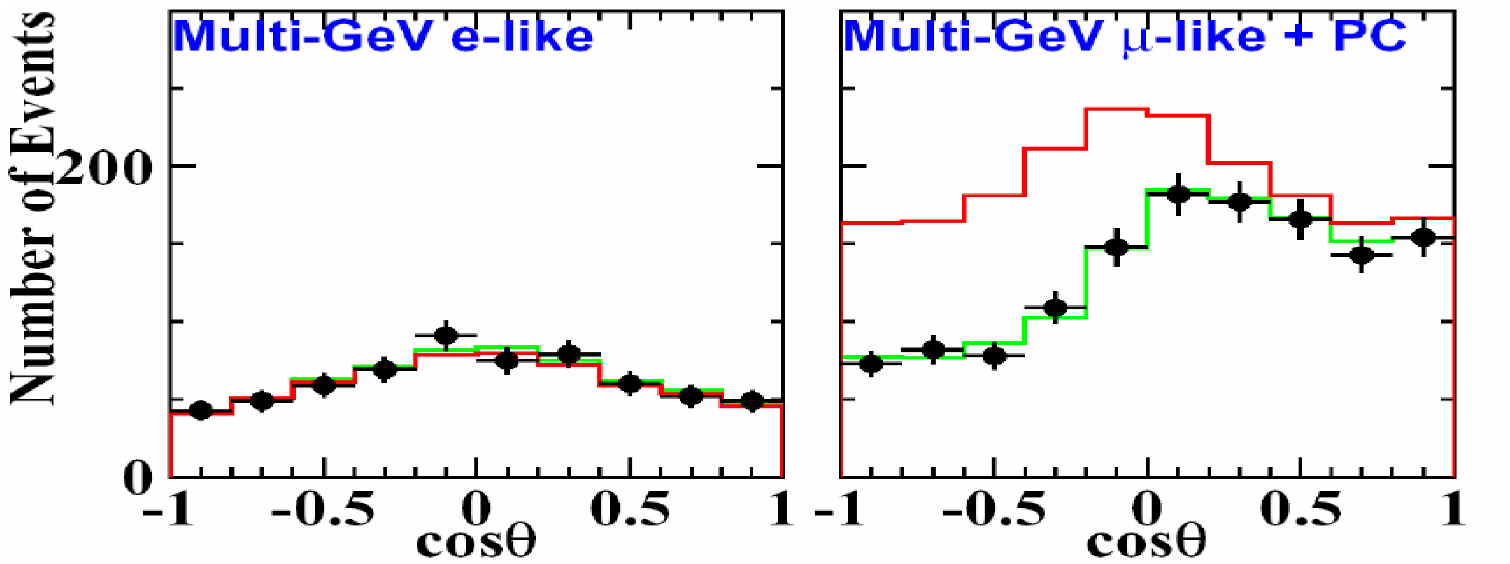
Expect $\dfrac{N\left(\nu_\mu + \bar{\nu}_\mu\right)}{N\left(\nu_e + \bar{\nu}_e\right)} \approx 2$

At higher energies, the muons can reach the ground before decaying so ratio increases

$$R = \frac{(\mu / e)_{Data}}{(\mu / e)_{MC}}$$

R ~ 0.6 - 0.7





The Atmospheric Neutrino Anomaly

Neutrino Flavour Oscillations

Mixing

CKM Mechanism

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

$$d' = d\cos\theta_c + s\sin\theta_c$$
$$s' = -d\sin\theta_c + s\cos\theta_c$$

In the quark sector, the flavour eigenstates (those states which couple to the W/Z) are not identical to the mass eigenstates (those states which are eigenstates of the Hamiltonian)

Weak states → $$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 0.97 & 0.23 & 0.003 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 0.99 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$ ← Mass states

Mixing

CKM Mechanism

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

$$d' = d\cos\theta_c + s\sin\theta_c$$
$$s' = -d\sin\theta_c + s\cos\theta_c$$

In the quark sector, the flavour eigenstates (those states which couple to the W/Z) are not identical to the mass eigenstates (those states which are eigenstates of the Hamiltonian)

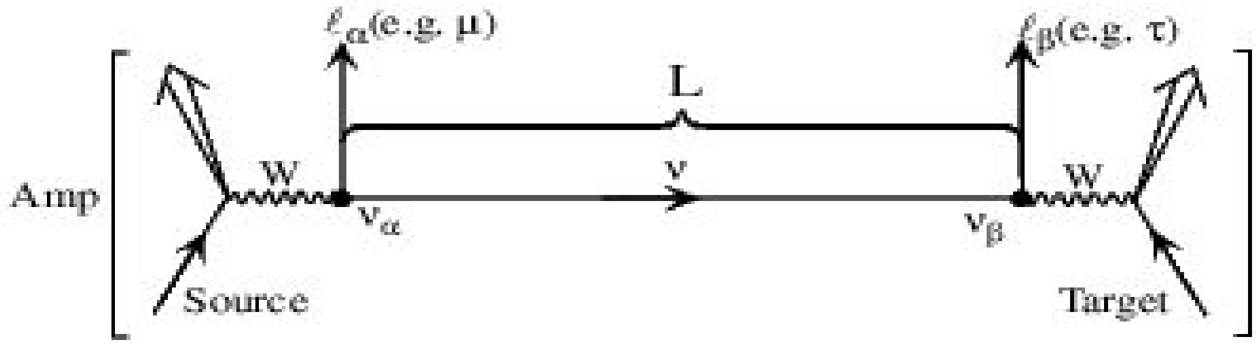
Weak states →

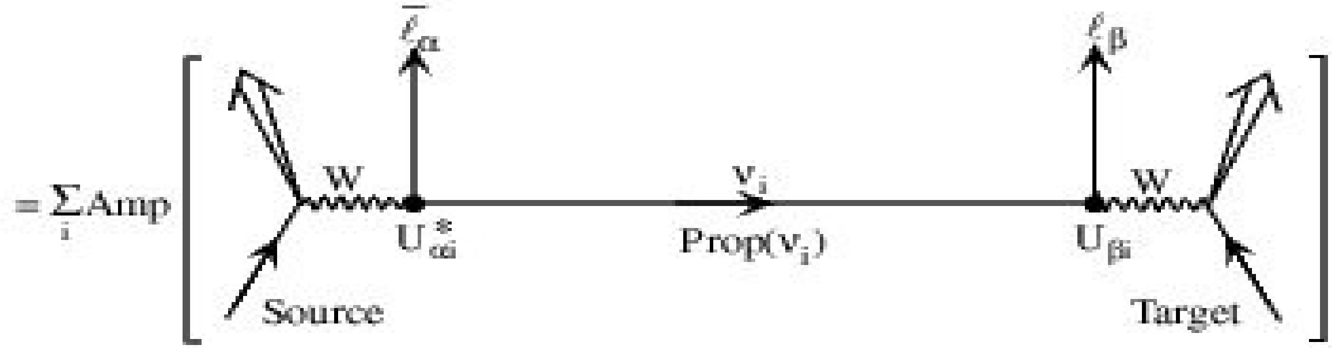
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

← Mass states

Unitary mixing matrix

Neutrino Oscillations





$$Prob(\nu_\alpha \rightarrow \nu_\beta) \propto \left|\sum_i U^*_{\alpha i} \mathrm{Prop}(\nu_i) U_{\beta i}\right|^2$$

If we don't know which mass state was created then the the amplitude involves a <u>coherent</u> superposition of ν_i states

$$Prob(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E})$$
$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E})$$

- If $\Delta m_{ij}^2 = 0$ then neutrinos don't oscillate
- Oscillation depends on $|\Delta m^2|$ - absolute masses cannot be determined
- If there is no mixing (If $U_{ai} = 0$) neutrinos don't oscillate
- One can detect flavour change in 2 ways : start with ν_α and look for ν_β (appearance) or start with ν_α and see if any disappears (disappearance)
- Flavour change oscillates with L/E. L and E are chosen by the experimenter to maximise sensitivity to a given Δm^2
- Flavour change doesn't alter total neutrino flux – it just redistributes it amongst different flavours (unitarity)

Two flavour oscillations

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \Rightarrow U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} \sin^2(\Delta m_{ij}^2 \frac{L}{4E})$$

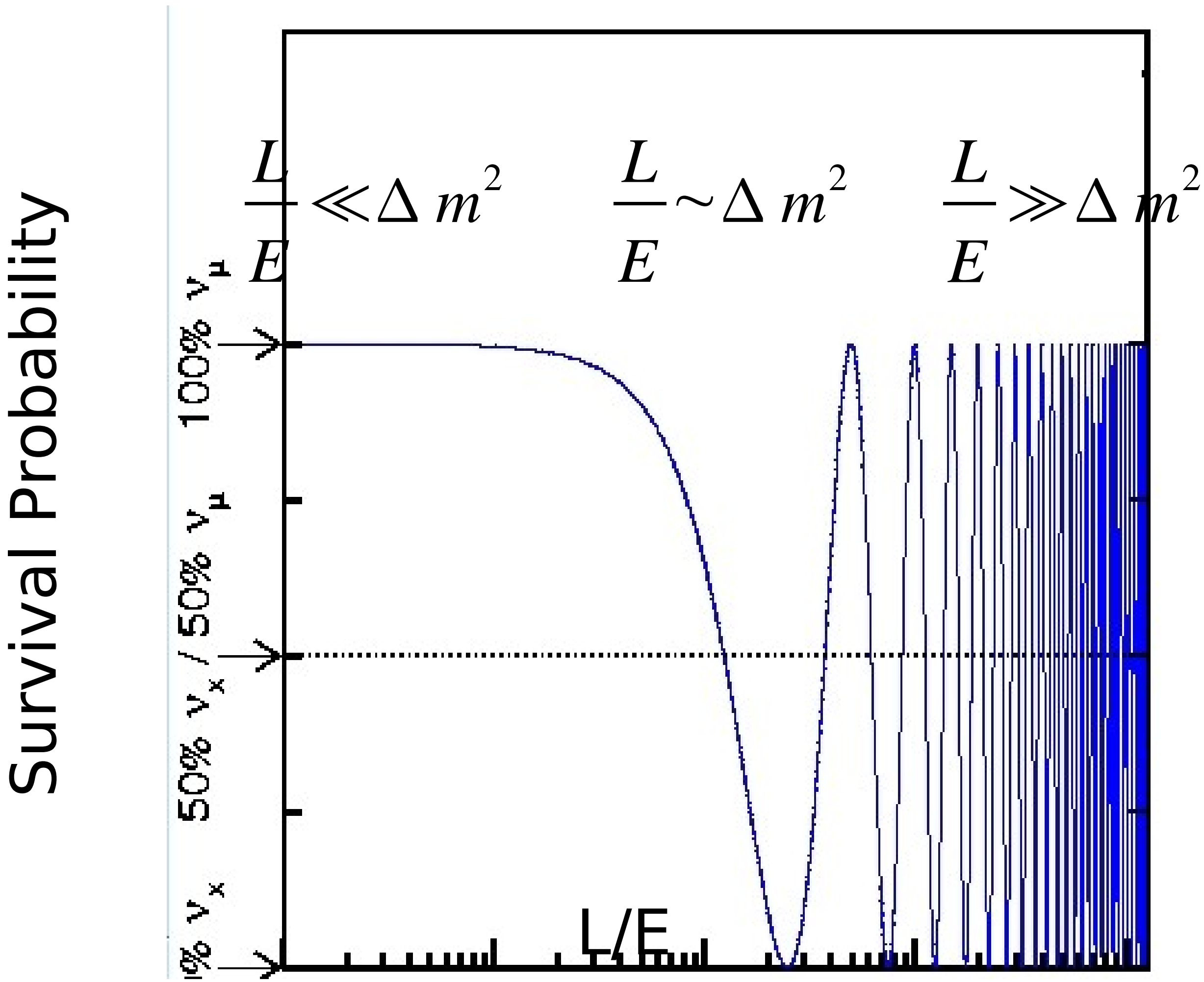
$P(\nu_\alpha \rightarrow \nu_\beta)$: Appearance Probability

$P(\nu_\alpha \rightarrow \nu_\alpha)$: Survival Probability

$$P(\nu_\alpha \rightarrow \nu_\beta) = -4(U_{\alpha 1} U_{\beta 1} U_{\alpha 2} U_{\beta 2}) \sin^2(\Delta m_{ij}^2 \frac{L}{4E})$$

$$. = \sin^2(2\theta) \sin^2(1.27 \Delta m^2 (eV^2) \frac{L(km)}{E(GeV)})$$

(changing to useful units)



$$P(\nu_\alpha(0) \rightarrow \nu_\alpha(x)) = 1 - \sin^2(2\theta)\sin^2(1.27\,\Delta m^2 \frac{(L/km)}{(E/GeV)})$$

Question : What would you observe if you were able to know what mass state propagated from source to detector?

Three Flavour Oscillation

The three flavour case is more complicated, but no different

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

U is the Pontecorvo-Maskawa-Nakayama-Sakata (PMNS) matrix

$$Prob(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E})$$

$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E})$$

Oscillation parameters

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

2 independent Δm^2

$$Prob(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re (U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 (\Delta m^2_{ij} \frac{L}{4E})$$

$$+ 2 \sum_{i>j} \Im (U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin (\Delta m^2_{ij} \frac{L}{2E})$$

Oscillation parameters

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

Three angles

$$Prob(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E})$$

$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E})$$

Oscillation parameters

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

CP violating phase

$$Prob(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E})$$

$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E})$$

Oscillation parameters

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$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

Extra Majorana phases

The extra Majorana matrix does not affect flavour oscillation processes.....so is usually dropped. However it will affect the interpretation of neutrinoless double beta decay results

Explaining the solar data

Testing the oscillation hypothesis

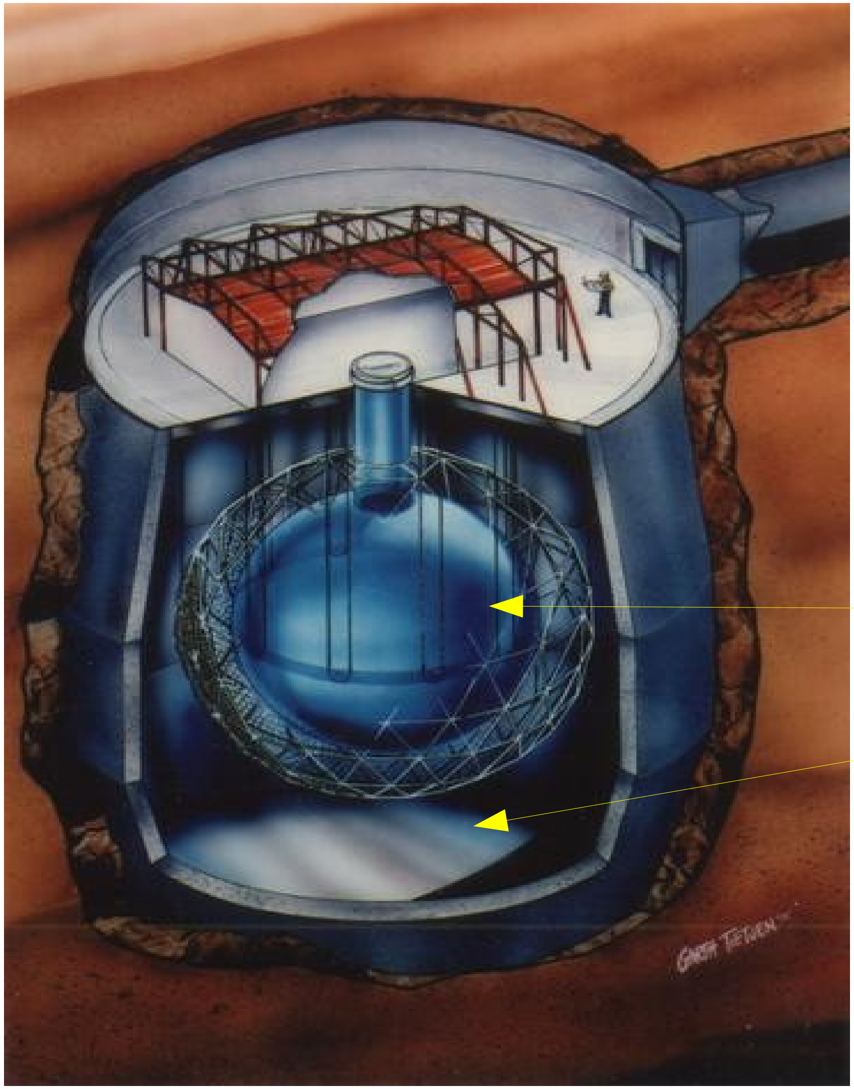
Solar neutrino problem

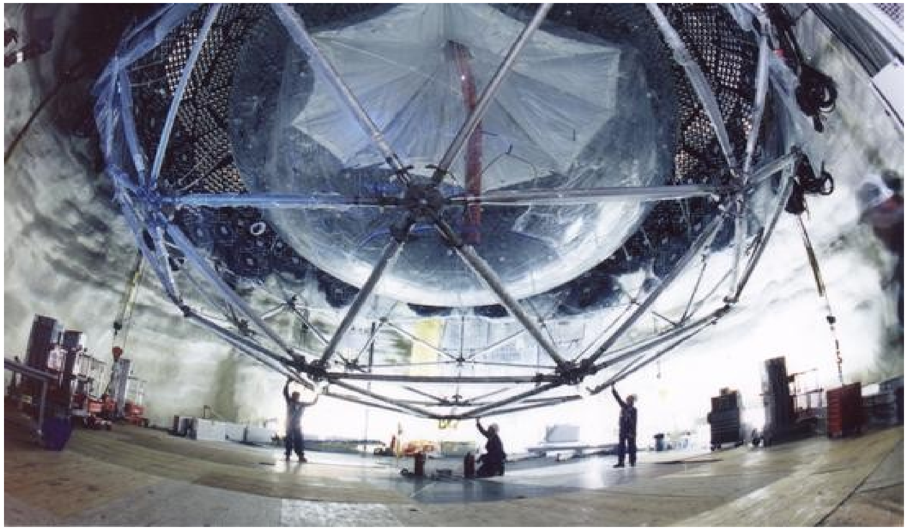
ν_e from sun would change to ν_μ or ν_τ . However these have too little energy to interact via the charged current, and all the detectors are only sensitive to charge current interactions.

Non-ν_e component would effectively disappear, reducing the apparent ν_e flux.

Proof : Neutral current event rate shouldn't change.

Sudbury Neutrino Observatory





1000 tonnes of D_20

6500 tons of H_20

Viewed by 10,000 PMTS

In a salt mine 2km underground in Sudbury, Canada

SNO

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

- Q = 1.445 MeV
- good measurement of ν_e energy spectrum
- some directional info $\propto (1 - 1/3 \cos\theta)$
- ν_e only

Produces Cherenkov Light Cone in D_2O

ν_e

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

- Q = 2.22 MeV
- measures total ^8B ν flux from the Sun
- equal cross section for all ν types

n captures on deuteron
$^2H(n, \gamma)^3H$
Observe 6.25 MeV γ

$\nu_e+\nu_\mu+\nu_\tau$

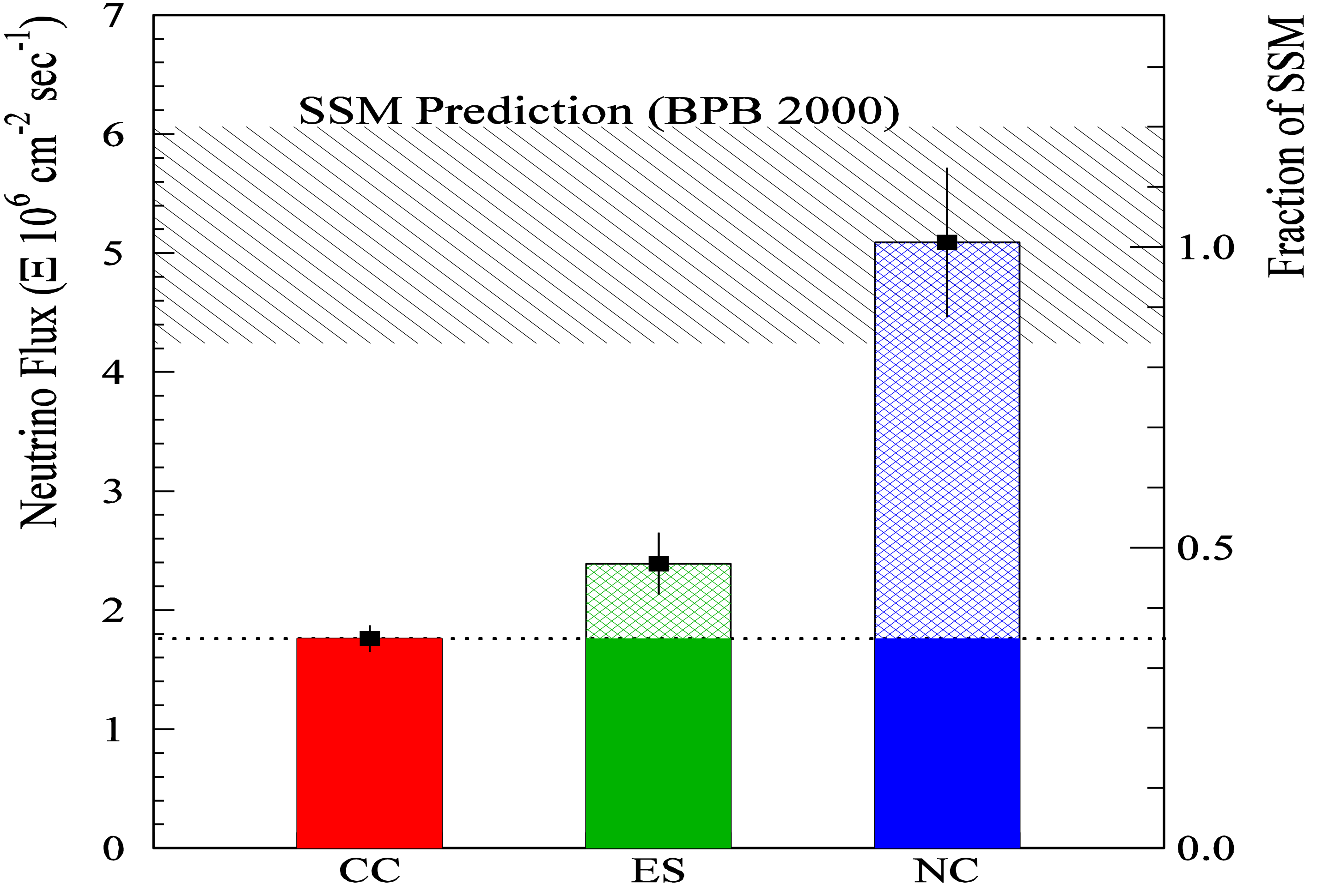
ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity

Produces Cherenkov Light Cone in D_2O

$\nu_e+0.15*(\nu_\mu+\nu_\tau)$

SNO Results



5.3 σ appearance of $\nu_{\mu\tau}$ in a ν_e beam

Roughly 70% of ν_e oscillates away

Naively…

First instinct is to assume that neutrinos leave the sun as ν_e and oscillate on their way to the earth. Assuming this

$$L \sim 10^8\,km\,,\ E_\nu < 10\,MeV \rightarrow \Delta m^2 \sim 3\times10^{-10}\,eV^2$$

Naively...

First instinct is to assume that neutrinos leave the sun as ν_e and oscillate on their way to the earth. Assuming this

$$L \sim 10^8\, km,\, E_\nu < 10\, MeV \rightarrow \Delta m^2 \sim 7 \times 10^{-5}\, eV^2$$

Naively…

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First instinct is to assume that neutrinos leave the sun as ν_e and oscillate on their way to the earth. Assuming this

$$L \sim 10^8\,km,\ E_\nu < 10\,MeV \rightarrow \Delta m^2 \sim \boxed{7 \times 10^{-5}\ eV^2}$$

Oscillations come from phase difference between mass states. In a vacuum the phase diff comes from free particle Hamiltonian. In a material there are interaction potentials as well

$$-i\hbar\frac{\partial\psi}{\partial t} = \boxed{E\psi} = \frac{-\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} \rightarrow -i\hbar\frac{\partial\psi}{\partial t} = \boxed{(E+V)}\psi = \frac{-\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2}$$

$$E^2 - p^2 = m_{vac}^2 \rightarrow (E+V)^2 - p^2 = m_{mat}^2 \rightarrow \boxed{m_{mat} \approx \sqrt{m_{vac}^2 + 2EV}}$$

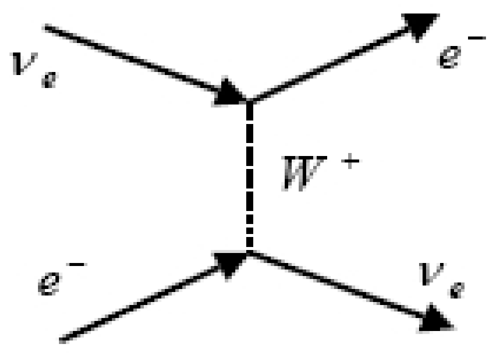
c.f. effective mass of an electron in a semiconductor or light in glass

Oscillations in Matter

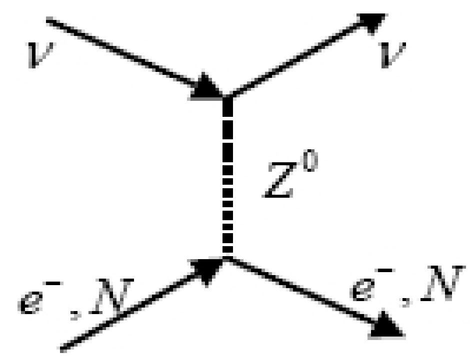
Electrons exist in standard matter – μ/τ do not. Electron neutrinos travelling in matter can experience an extra charged current interaction that other flavours cannot.

$$V_W = \sqrt{2}\, G_F N_e$$

Interaction Potential



ν_e



$\nu_e,\ \nu_\mu,\ \nu_\tau$

$$V_Z = -\frac{\sqrt{2}}{2} G_F N_n$$

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_M)\sin^2\left(\frac{\Delta m_M^2 L}{4E}\right)$$

Oscillation probability modified by matter effects

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

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

$$\zeta = \frac{2\sqrt{2}\, G_F N_e E}{\Delta m_V^2}$$

Implications

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - \zeta)^2} \qquad \zeta = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{Vac}}$$

- If $\Delta m^2_{Vac} = 0$ or matter is very dense, $\zeta = \infty$ and $\theta_m = 0$
- Similarly, if $\theta_{vac}=0$, then $\theta_M = 0 \Rightarrow$ need mixing in vacuum
- If there is no matter, then $\zeta = 0$ and we have vacuum mixing
- At a particular electron density, dependent on Δm^2,

$$\zeta = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2} = \cos 2\theta \;\Rightarrow\; \sin^2 2\theta_M = 1$$

Even if the vacuum mixing angle is tiny, there is a density for which the matter mixing angle is maximal

Mass heirarchy

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$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - \zeta)^2} \qquad \zeta = \frac{2\sqrt{2} G_F N_e E}{\Delta m_V^2}$$

If mass of v_1 < mass of v_2, $\Delta m_V^2 = m_1^2 - m_2^2 < 0$

$$\zeta = -\frac{2\sqrt{2} G_F N_e E}{|\Delta m^2|} \rightarrow \sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta + |\zeta|)^2}$$

Positive definite – no resonance

If mass of v_1 > mass of v_2, $\Delta m^2 = m_1^2 - m_2^2 > 0$

$$\zeta = \frac{2\sqrt{2} G_F N_e E}{|\Delta m^2|} \rightarrow \sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - |\zeta|)^2}$$

Mass heirarchy

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

$$\zeta = \pm \frac{2\sqrt{2} G_F N_e E}{|\Delta m_V^2|}$$

The effect of matter on neutrino oscillations can be used to measure the mass hierarchy.

This is about the only way we know how to do this.

Mixing matrix

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Solar sector

$$\theta_{e\mu} = 32.5^{o} \pm 2.4^{o}$$

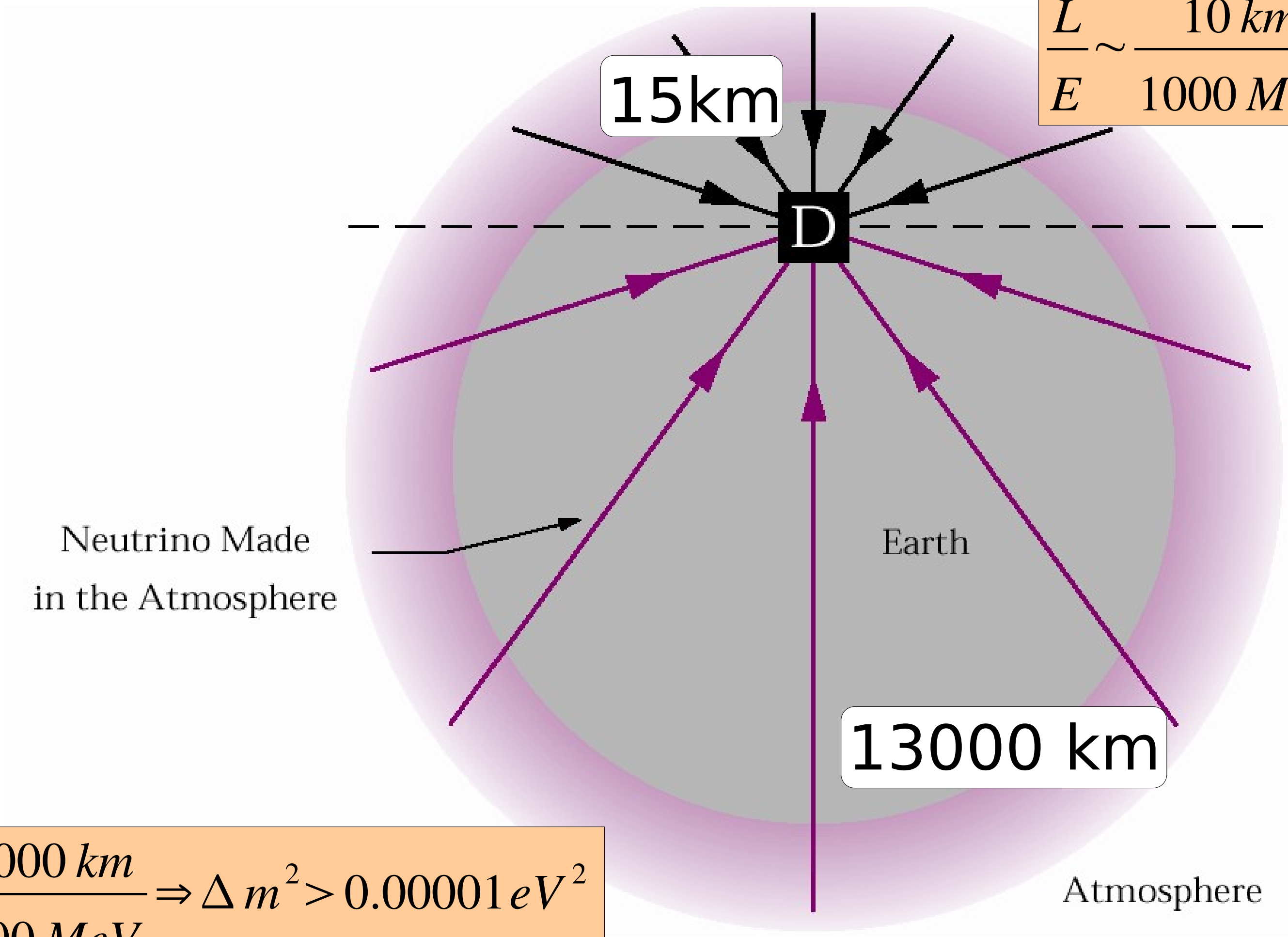
$$\Delta m_{12}^{2} = +7.9 \times 10^{-5}\, eV^{2}$$

Explaining the atmospheric data

Cosmic Labs

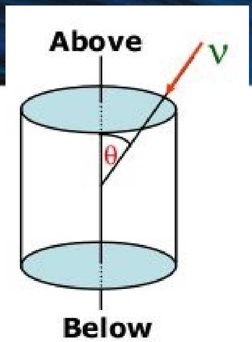
$\cos\theta_{zenith} = 1.0$

$$\frac{L}{E} \sim \frac{10\,km}{1000\,MeV} \Rightarrow \Delta m^2 > 0.01\,eV^2$$

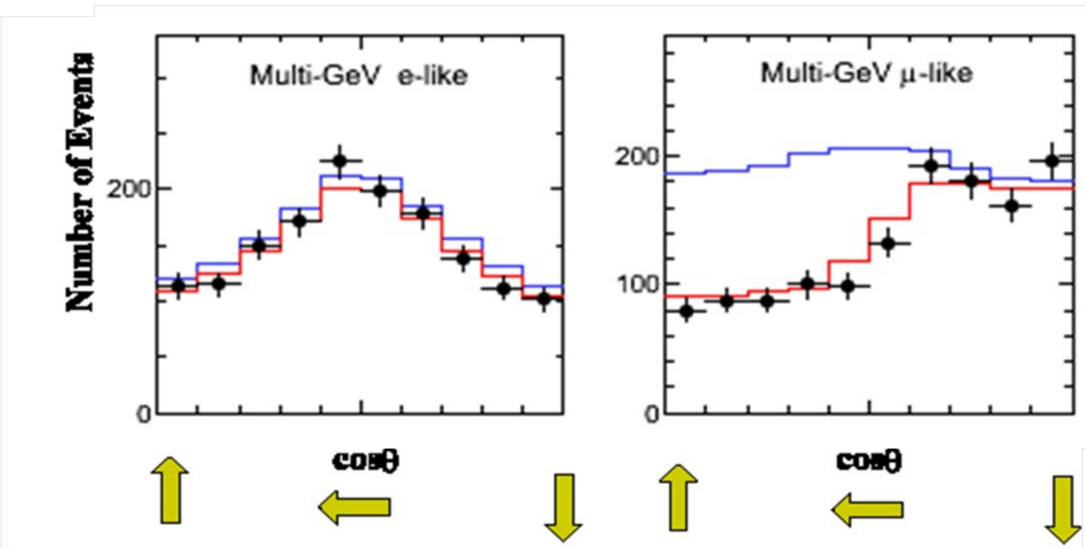


$$\frac{L}{E} \sim \frac{10000\,km}{1000\,MeV} \Rightarrow \Delta m^2 > 0.00001\,eV^2$$

$\cos\theta_{zenith} = -1.0$



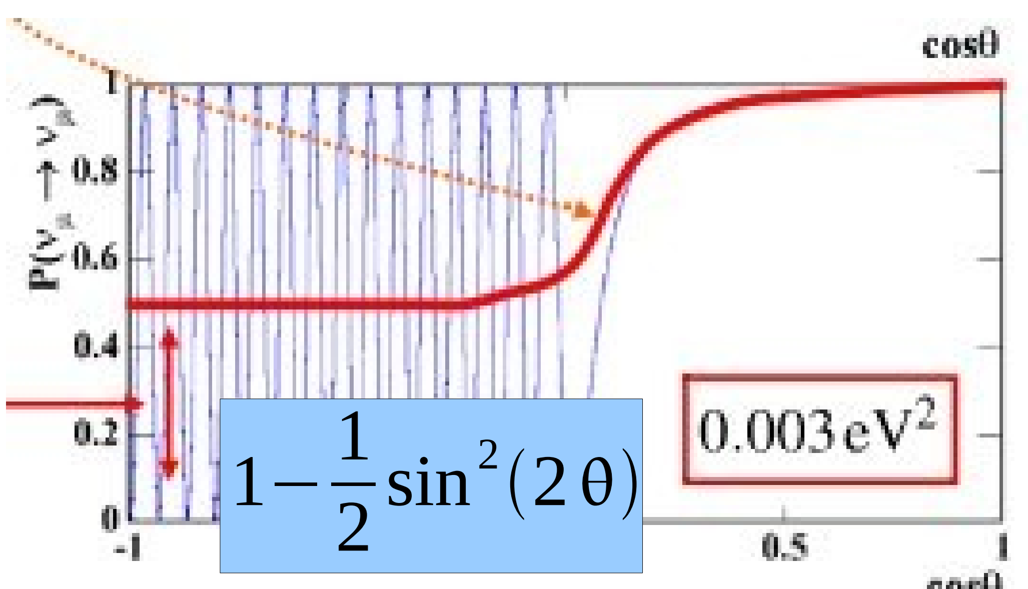
Atmospheric results



- Prediction for ν_e rate agrees with data.
- ν_μ disappear at large baseline consistent with $\nu_\mu \rightarrow \nu_\tau$
- Don't detect ν_τ as

-below τ mass threshold

-SuperK is awful at τ detection



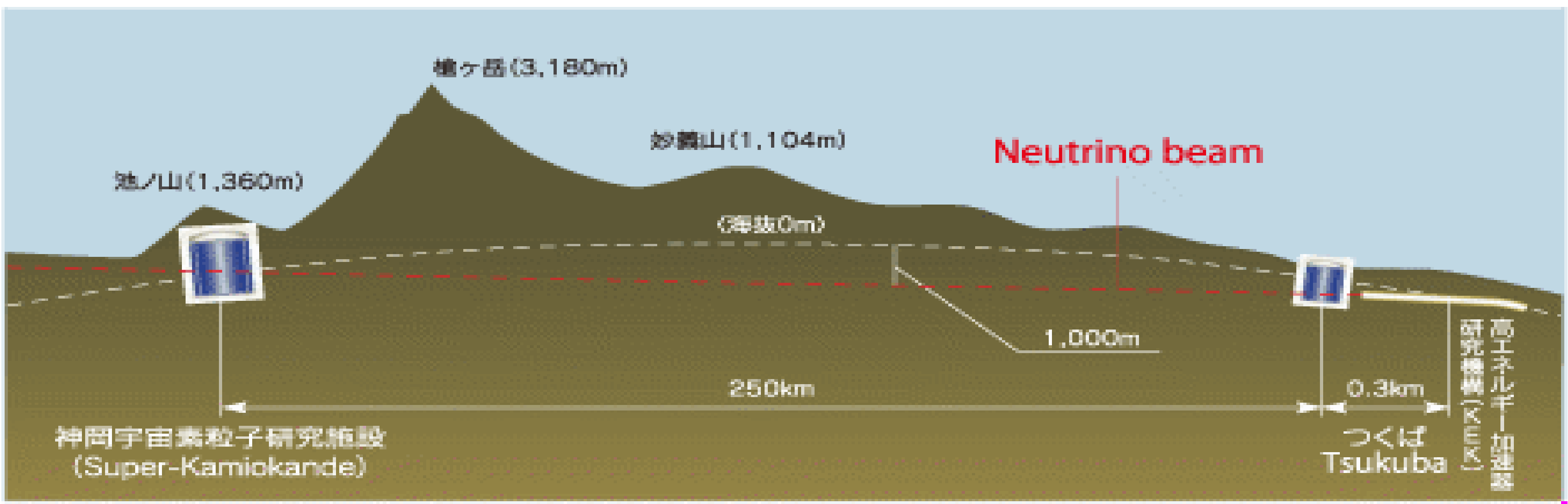
$$|\Delta m^2_{atmos}| \approx 0.0025\,eV^2$$

$$\sin^2(2\theta_{atmos}) \approx 1.0$$

Accelerator Cross-check

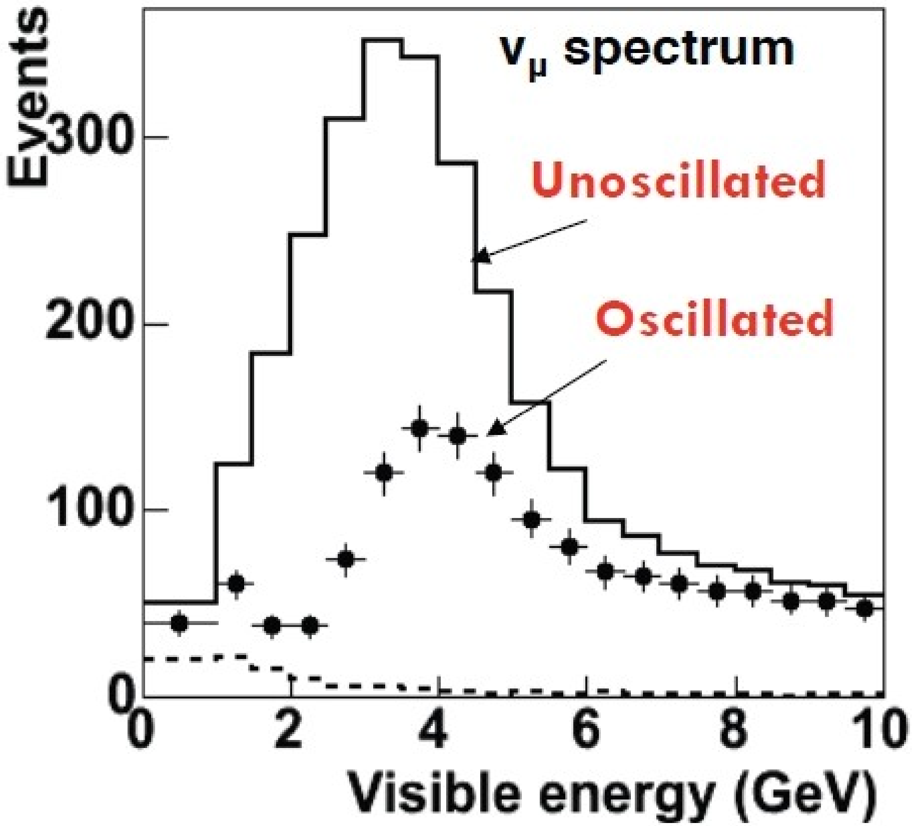
$$\Delta m^2_{atmos} \approx 3\times 10^{-3}\, eV^2 \rightarrow L/E \approx 400\, km\, GeV^{-1}$$

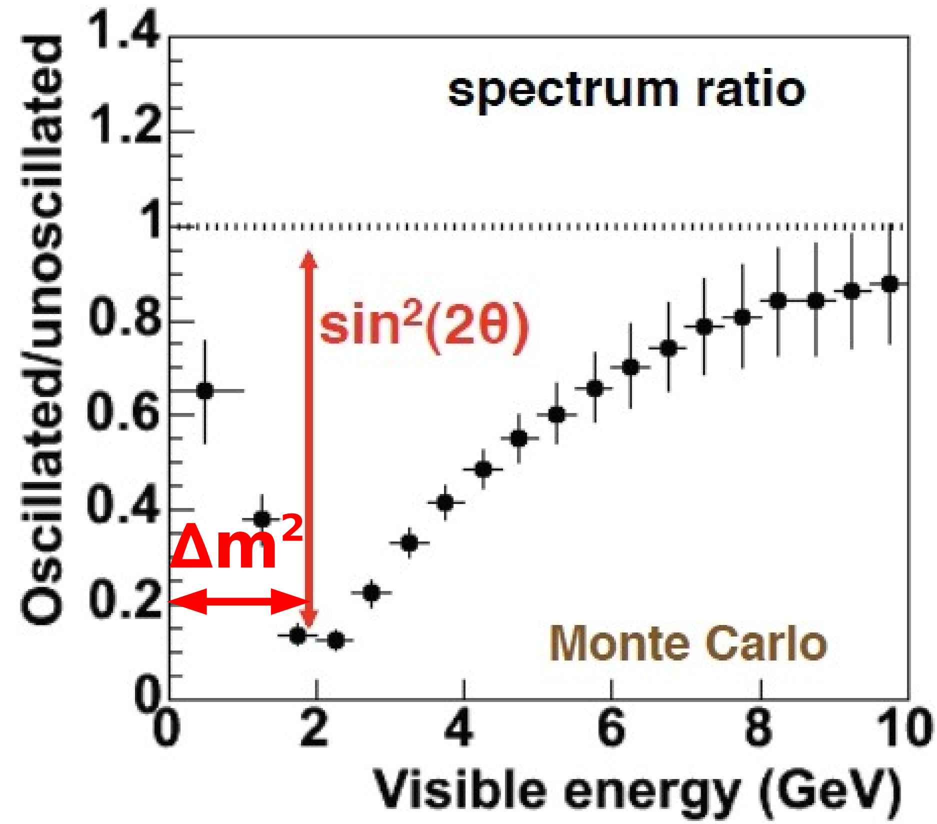
$$L = 250\, km \rightarrow E_\nu \approx 0.6\, GeV$$



Beam events tagged using GPS at both near and far detector sites

Disappearance Experiments



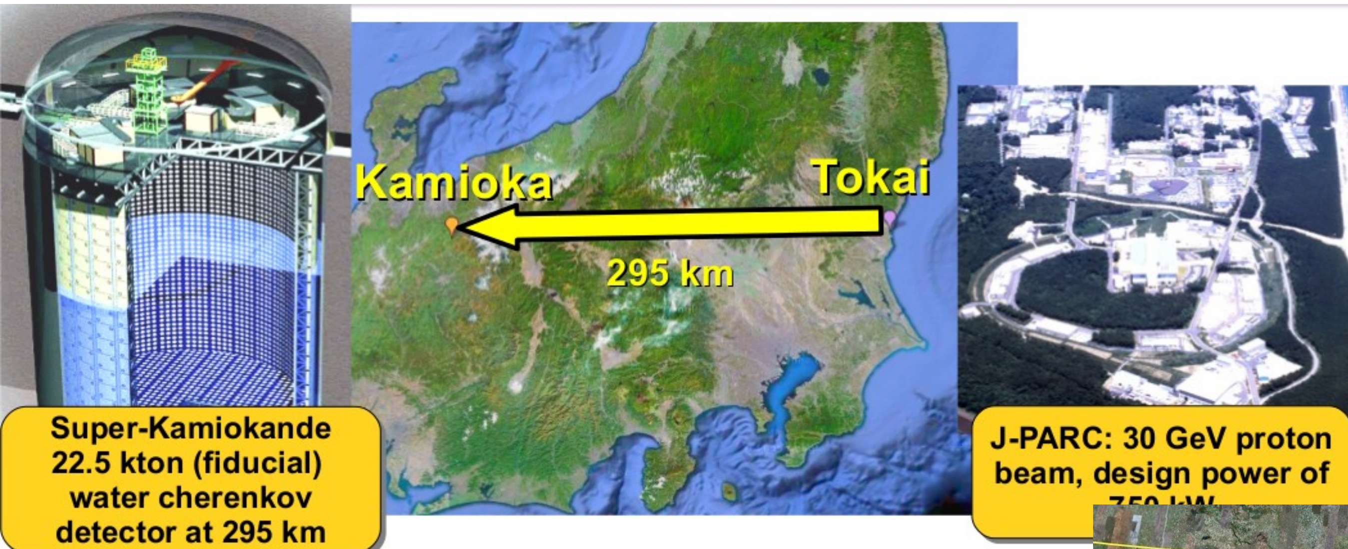


$$P(\nu_\alpha \to \nu_\alpha) \to \frac{\Phi_\nu(@FD)}{\Phi_\nu(@ND)}$$

Φ_ν : Neutrino Flux

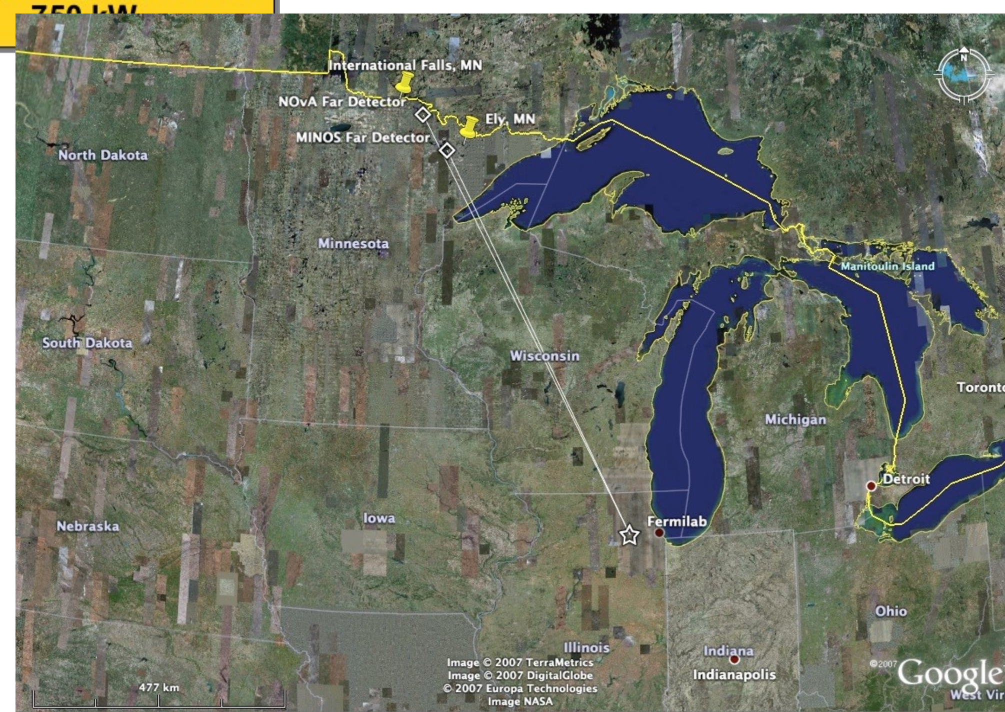
Use Near Detector to measure $\Phi_\nu(@ND)$

T2K and NOVA

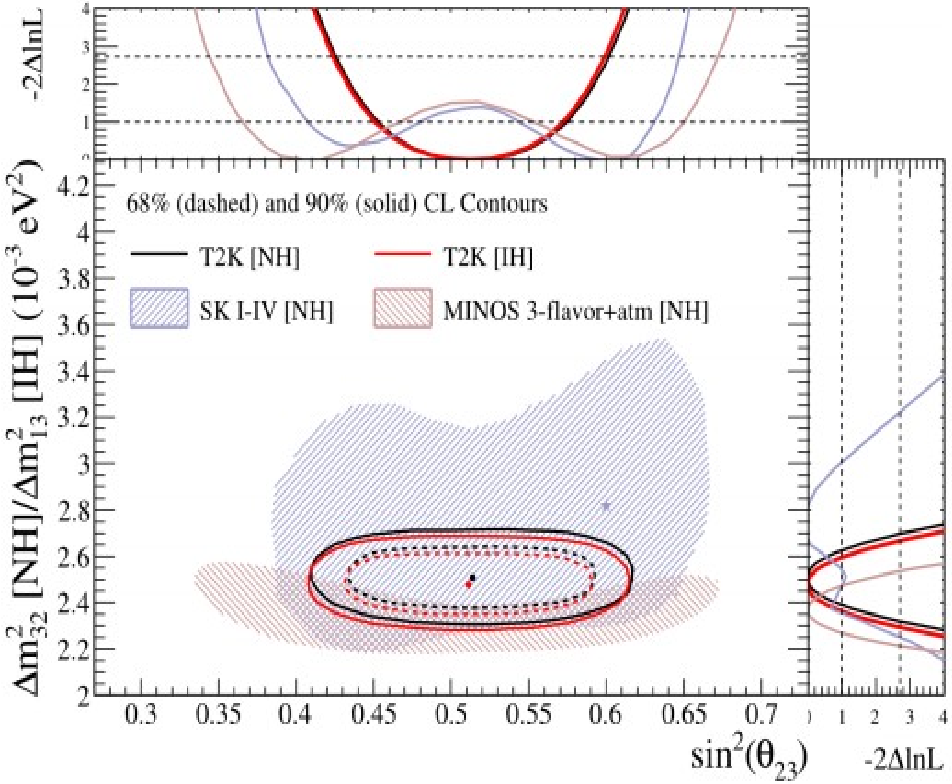


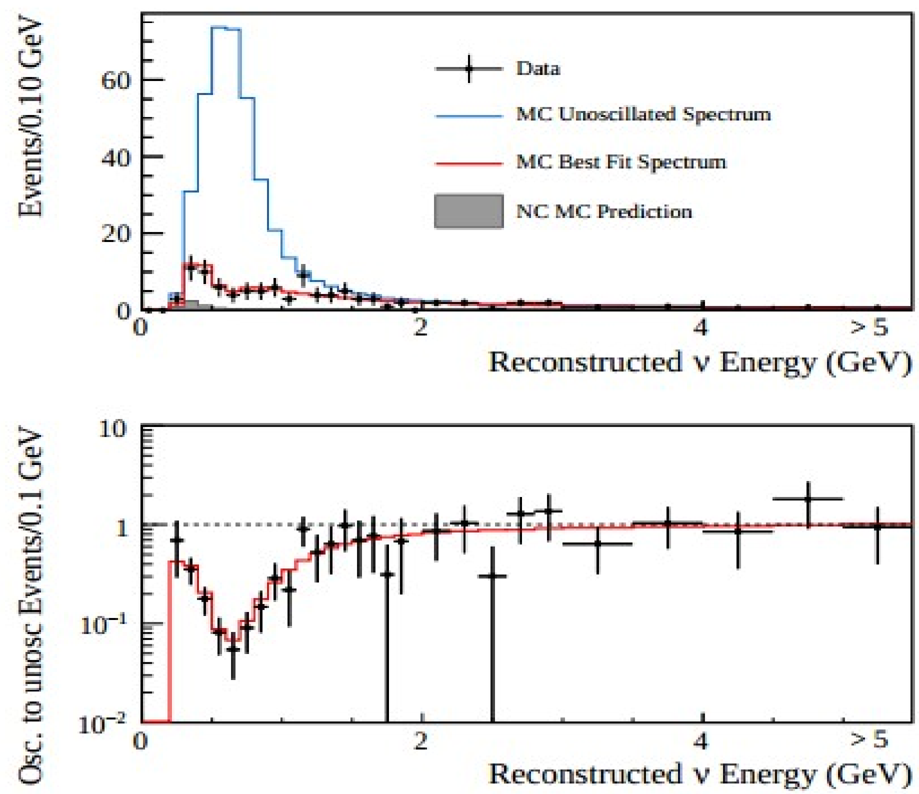
- JPARC to Kamioka
- L = 295 km
- E_ν ~ 0.6 GeV
- Far Det : 22.6 kton water Cerenkov detector

- Fermilab to Ash River, MN
- L = 810 km
- E_ν ~ 2.0 GeV
- Far Det : 14 kton of liquid scintillator (in bars)



T2K Disappearance





$$\frac{\#\,events\,observed}{\#\,events\,expected} = P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$|\Delta m^2_{23}| = (2.51 \pm 0.1)\times 10^{-3}\, eV^2$$

$$\sin^2(\theta_{23}) = 0.514^{+0.055}_{-0.056} \to \theta_{23} = 45.8 \pm 3.2$$

(best fit)

Mixing matrix

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Solar sector : $\nu_\mu \rightarrow \nu_e$

$$\theta_{e\mu} = 33.7^{o} \pm 1.1^{o}$$

$$\Delta m_{12}^2 = +(7.54 \pm 0.24) \times 10^{-5}\, eV^2$$

Atmospheric sector

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

$$\theta_{\mu\tau} = 42^{o} \pm 3.0^{o}$$

$$\Delta m_{23}^2 = \left|(2.43 \pm 0.06) \times 10^{-3}\right| eV^2$$

How do we measure θ_{13}?

$\nu_\mu \rightarrow \nu_e$ oscillations with atmospheric L/E

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 (1.27 \Delta m^2_{23} \frac{L}{E})$$

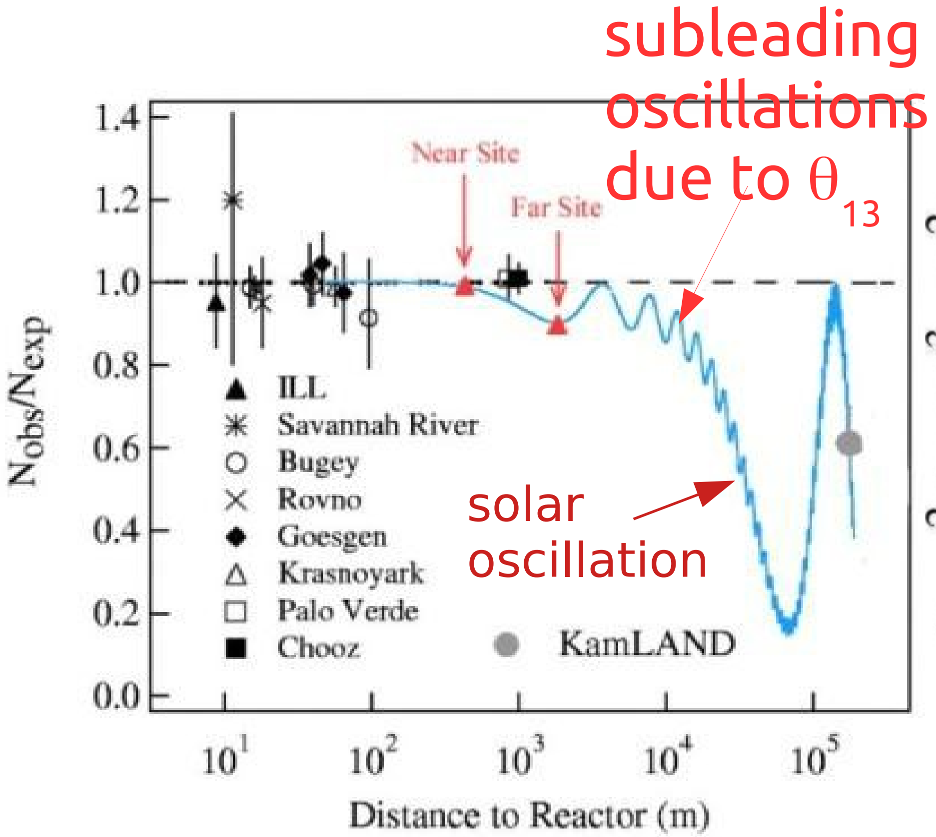
ν_e appearance in a ν_μ beam – ideal for *accelerator experiments*

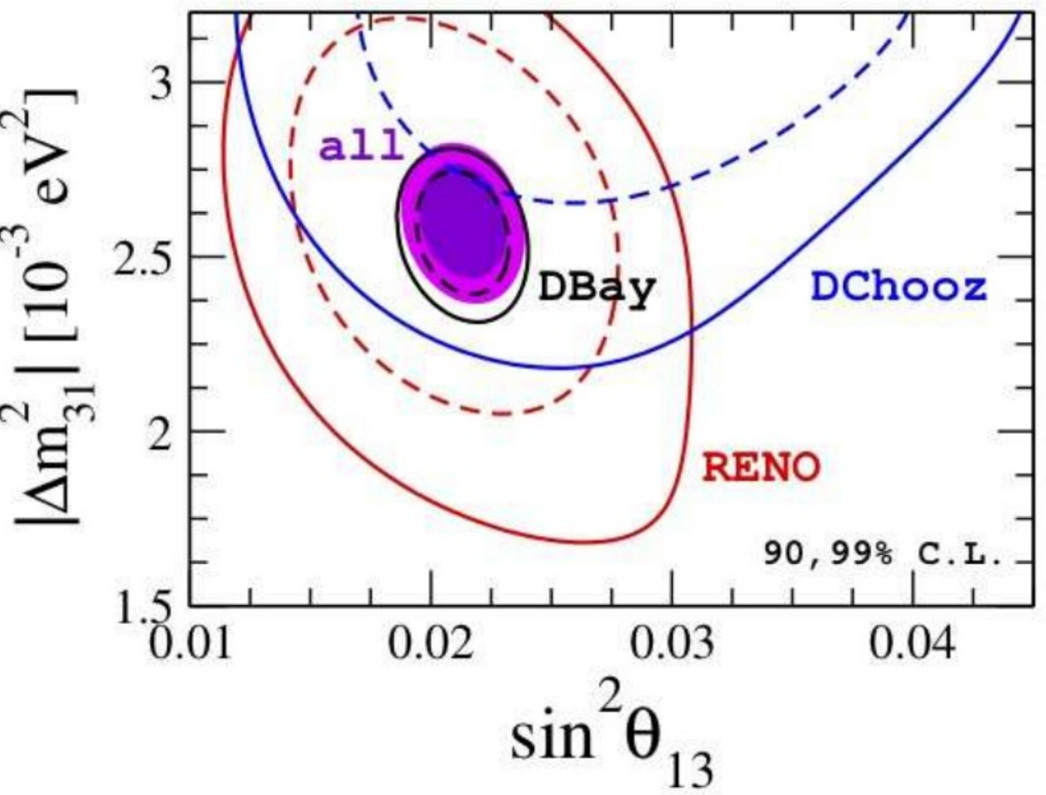
$\overline{\nu}_e \rightarrow \overline{\nu}_x$ disappearance oscillations with atmospheric L/E

$$p(\overline{\nu}_e \rightarrow \overline{\nu}_x)\, 1 - \sin^2(2\theta_{13}) \sin^2(1.27 \Delta m^2_{23} \frac{L}{E})$$

$\overline{\nu}_e$ disappearance – ideal for *reactor experiments*

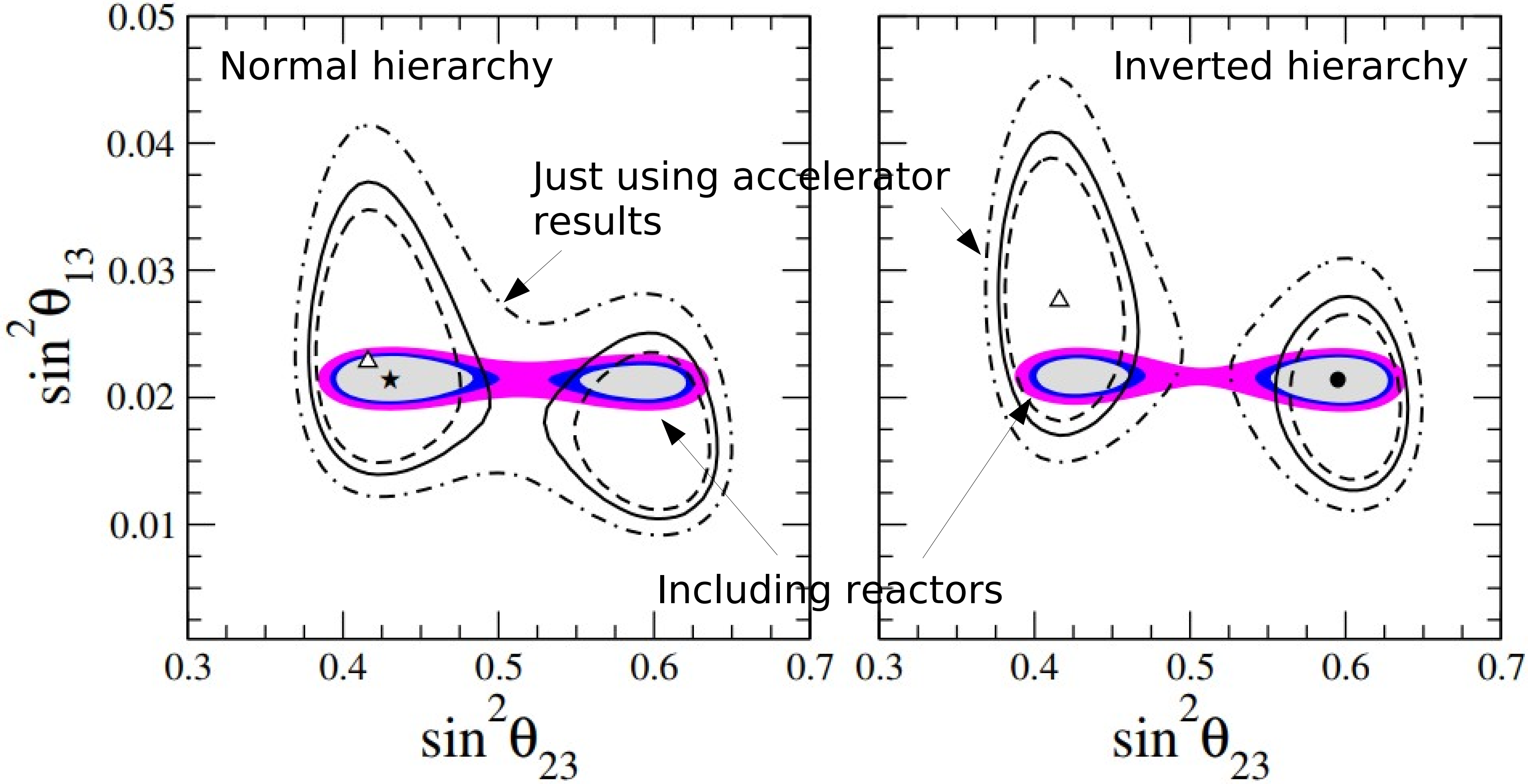
θ_{13} from reactors





$$\theta_{13} = (8.44(41) \pm 0.16)^\circ \, (\mathrm{NO(IO)})$$

Global results



3-Neutrino Mixing

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Solar sector

$\nu_e \rightarrow \nu_\mu$

$\theta_{12} = 34.5^\circ \pm 1.1^\circ$

$\Delta m^2_{12} = +7.56 \times 10^{-5}\, eV^2$

13 Sector

$\nu_\mu \rightarrow \nu_e$

$\theta_{13} = 8.44^\circ \pm 0.16^\circ$

$\Delta m^2_{23} = |2.52 \times 10^{-3}|\, eV^2$

Atmospheric sector

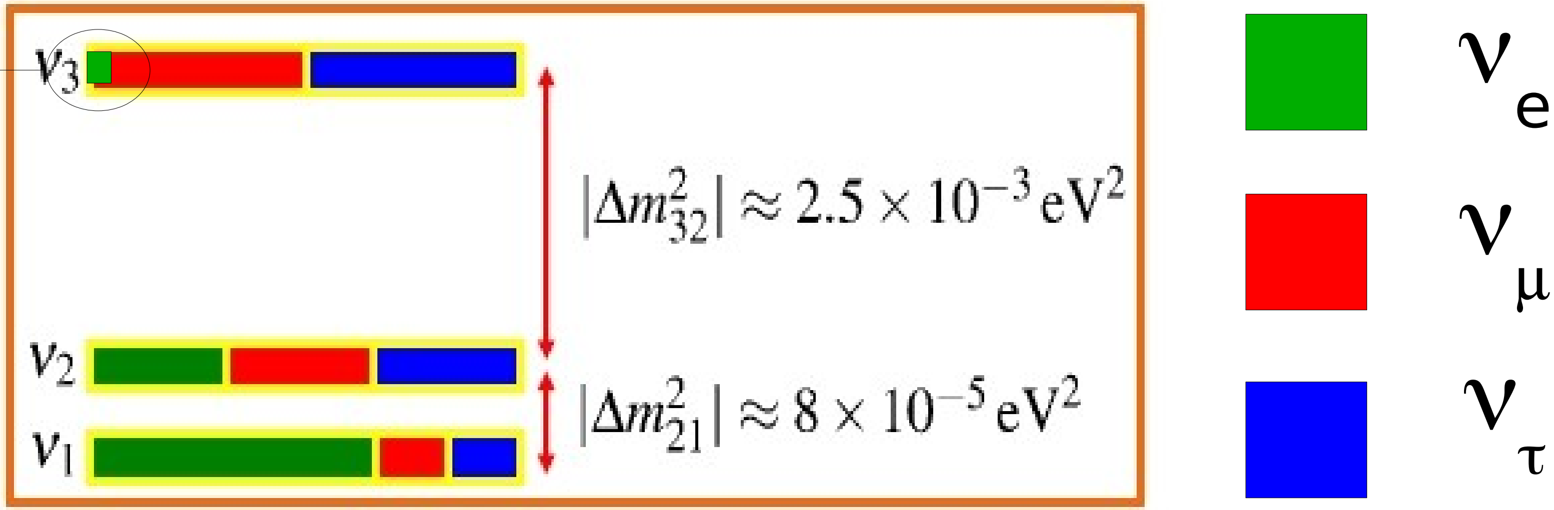
$\nu_\mu \rightarrow \nu_\tau$

$\theta_{23} = 41.0(50.5)^\circ \pm 1.1^\circ$

$\Delta m^2_{23} = |2.52 \times 10^{-3}|\, eV^2$

Summary of Current Knowledge

θ_{13} : how much ν_e is in ν_3



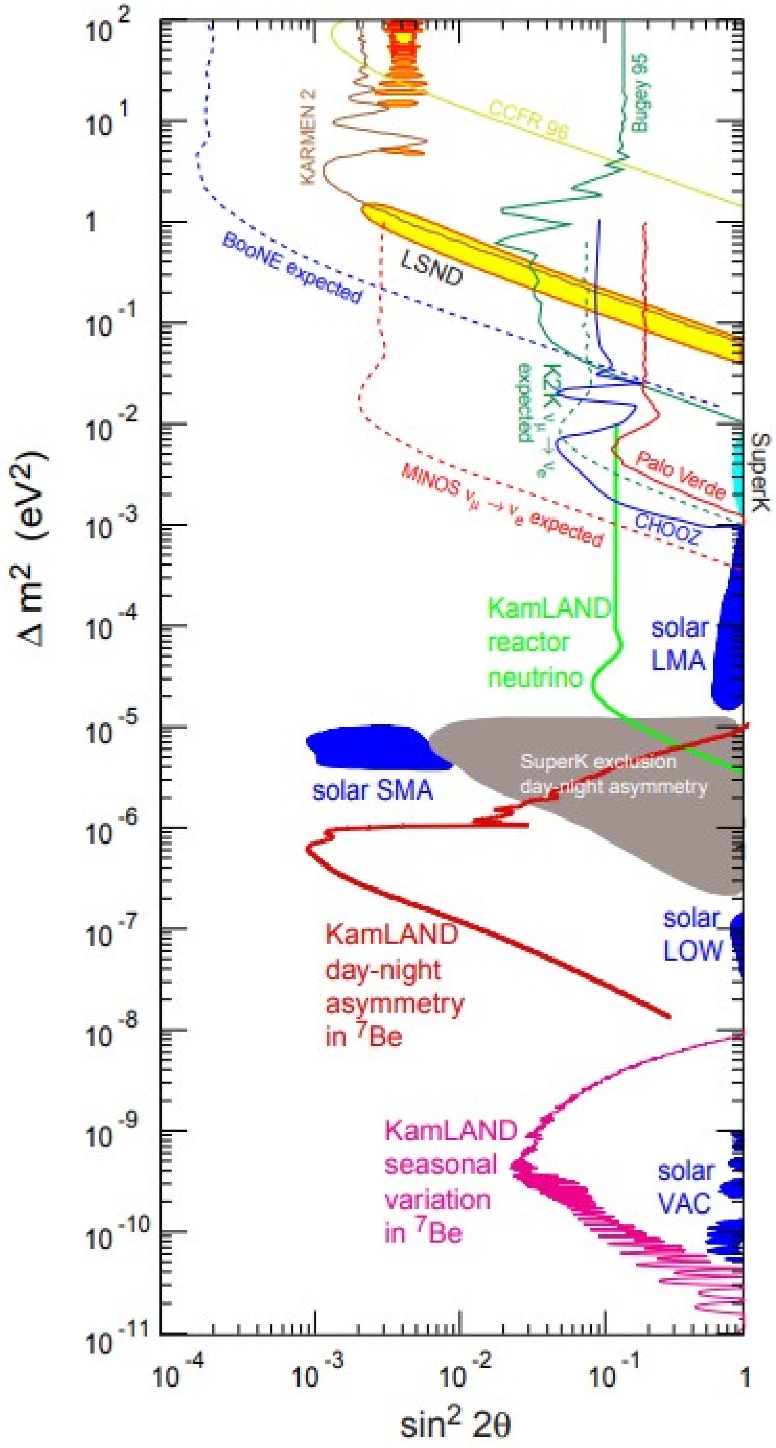
$$U_{MNSP} \approx \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.5 & 0.6 \\ 0.4 & 0.5 & 0.7 \end{pmatrix}$$

Some elements only known to 10-30%

Very very different from the quark CKM matrix

Comparison

State of play : Yr 2000



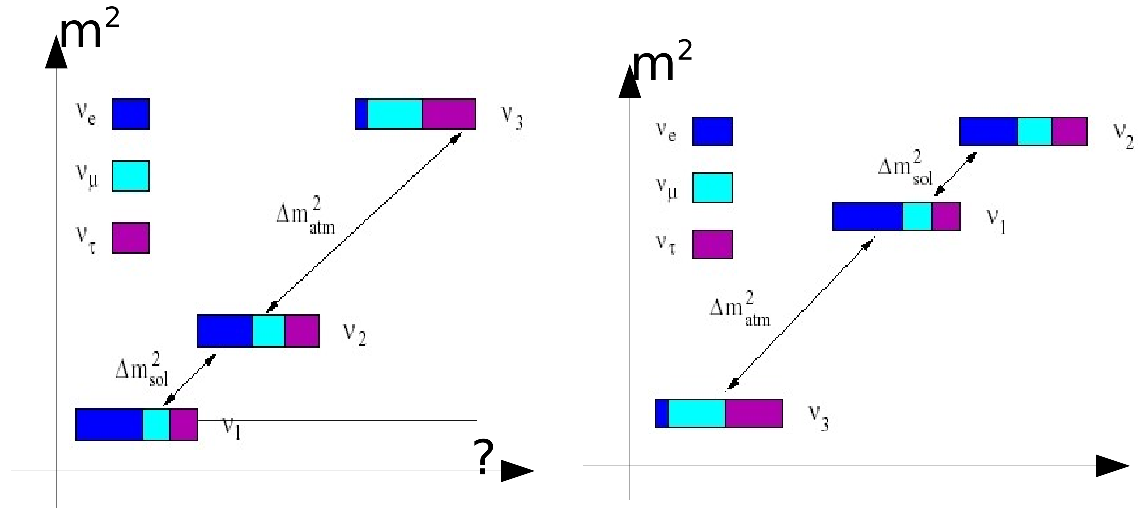
The Quest

WARWICK
THE UNIVERSITY OF WARWICK

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

Value of δ?

Normal or Inverted mass heirarchy?



- Better estimates of the oscillation parameters using accelerators
- Is θ_{23} maximal?
- Is the neutrino Majorana?
- What is the absolute mass?

$$U_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.7 & 0.6 \\ 0.4 & 0.5 & 0.7 \end{pmatrix}$$

?

$$U_{CKM} = \begin{pmatrix} 0.975 & 0.222 & 0.004 \\ 0.221 & 0.97 & 0.04 \\ 0.01 & 0.04 & 0.999 \end{pmatrix}$$