THE WONDERFUL WORLD OF NEUTRINOS

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“· · · riddle wrapped in mystery inside an enigma” Winston Churchill

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- REACTOR NEUTRINOS
- COSMOLOGICAL NEUTRINOS
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INTRODUCTION

elementary fermions: quarks and leptons

$\uparrow$

neutrinos $\nearrow Q_S = 0$

$\rightarrow Q_{EM} = 0$

$\searrow Q_W \neq 0$

nucleus $\supset p, n$: mass $\sim$ 1 GeV $\qquad c = 1 = \hbar$

$$p = (uud), \quad n = (udd)$$

$\begin{pmatrix} u \\ d \end{pmatrix}$
= up quark with charge $+\frac{2}{3}|e|$, $m_u \sim$ 3 MeV
= down quark with charge $-\frac{1}{3}|e|$, $m_d \sim$ 7 MeV

Two more doublets $\begin{pmatrix} c \\ s \end{pmatrix}$ $\quad m_c \sim 1.2$ GeV, $\quad m_s \sim 120$ MeV

$\begin{pmatrix} t \\ b \end{pmatrix}$ $\quad m_t \sim 180$ GeV, $\quad m_b \sim 4.3$ MeV

Three generations or flavours.

$$\begin{array}{rcl} \text{Also,} & \begin{pmatrix} \nu_e \\ e \end{pmatrix} & m_e \sim 0.5 \text{ MeV} \\ & \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} & m_\mu \sim 105 \text{ MeV} \\ m_\nu =? & \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} & m_\tau \sim 1.8 \text{ GeV} \end{array}$$

+ antiparticles $\bar{f}$ for each f with the same mass.

Beta decay:

$$n \to p e^- \bar{\nu}_e$$

$$d(ud) \to u(ud) e^- \bar{\nu}_e$$

$$\begin{array}{rcl} (\bar{u}d): \pi^- \longrightarrow \nu^- \bar{\nu}_\mu & ; & \mu^- \longrightarrow e^- \bar{\nu}_e \nu_\mu \\ (u\bar{d}): \pi^+ \longrightarrow \mu^+ \nu_\mu & ; & \mu^+ \longrightarrow e^+ \nu_e \bar{\nu}_\mu \\ Z \longrightarrow \tau^+ \tau^- & ; & \tau^+ \longrightarrow \mu^+ (e^+) \nu_\mu (\nu_e) \bar{\nu}_\tau \\ & & \tau^- \longrightarrow \mu^- (e^-) \bar{\nu}_\mu (\bar{\nu}_e) \nu_\tau \end{array}$$

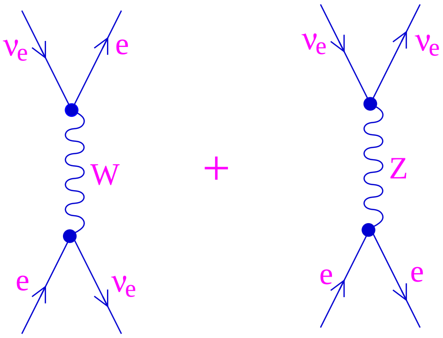
All sorts of neutrinos

Neutrino source	Description	Energy
Big Bang	Thermalized at 1.95°K. Undetected yet.	$\sim$ 10^{-4} eV
Stellar core	From nuclear reactions powering the star. Solar neutrinos detected.	$\sim$ 0.1 to 0 (10) MeV
Supernova	Detected from SN1987A.	10–30 MeV
Atmospheric	In a cosmic ray air-shower. Detected first in 1965 in Kolar Gold Fields, India.	sub-GeV to multi-GeV
Radioactivity on earth	Flux $\sim$ 10^6 cm^{-2} sec^{-1}. Can be of geophysical use	$\mathcal{O}$ (MeV)
Reactors	Antineutrinos from $n \longrightarrow pe^- \bar{\nu}_e$ICF in neutron-rich fissile nuclei.	$\sim$ 4 MeV
Accelerators	Neutrino beams at CERN, BNL, Fermilab, JHF.	sub-GeV to GeV

There can be additional cosmic sources of UHE neutrinos: AGN, GRB.

ICECUBE etector at South pole: 1 km^3 cubic lattice of phototubes.

Neutrinos may be Dirac particles, i.e. $\nu \neq \bar{\nu}$ or Majorana particles $\nu = \bar{\nu}$.

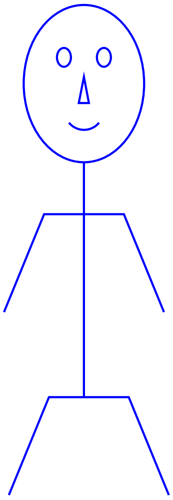


Neutrino scattering from matter electrons :

$\sigma \sim 10^{-44}$ cms for an MeV energy ν_e.

$$\lambda = 1/(N_e \sigma) \sim \pi/(2 N_e G_F^2 m_e E_\nu)$$

Mfp of such ν in lead = 1 light year. Yet neutrino flavour conversion can be significantly enhanced in 1000 kms. of earth matter.



$\xrightarrow[\text{in/sec}]{\text{Neutrinos}}$

10^{15} from Sun

10^{10} from radioactive rocks

10^{11} from all nulear power plants in the world

$\xrightarrow[\text{out/sec}]{\text{Neutrinos}}$

$\sim 4 \times 10^{6}$ from β – unstable ^{40}K in human body

- In the Standard Model neutrinos are massless and only $\nu_L^{e,\mu,\tau} = \frac{1}{2}(1-\gamma_5)\nu^{e,\mu,\tau}$ exist
- Almost all extensions of the Standard Model predict nonzero neutrino masses

Dirac ν has four components $\nu_L, {\nu_L}^C, N_R, {N_R}^C$.

$$\nu = \nu_L + N_R.$$

Dirac mass term $m_D \bar{\nu}\nu = m_D(\bar{\nu}_L N_R + \bar{N}_R \nu_L)$

Question: Why is $m_\nu \ll m_f \quad \forall f$.

See-saw Mechanism

$$\begin{array}{cc} & \begin{array}{cc} \nu_L & \bar{N}_R \end{array} \\ \begin{array}{c} \nu_L \\ \bar{N}_R \end{array} & \begin{bmatrix} 0 & m_D \\ m_D & M_N \end{bmatrix} \end{array} \rightarrow \begin{pmatrix} \sim \frac{m_D^2}{M_N} & 0 \\ 0 & \sim M_N \end{pmatrix}$$

$M_N \gg m_D = \mathcal{O}(m_f) \quad \uparrow$

large Majorana
mass for N_R

Now $m_\nu \sim m_D^2/M_N \ll m_D$.

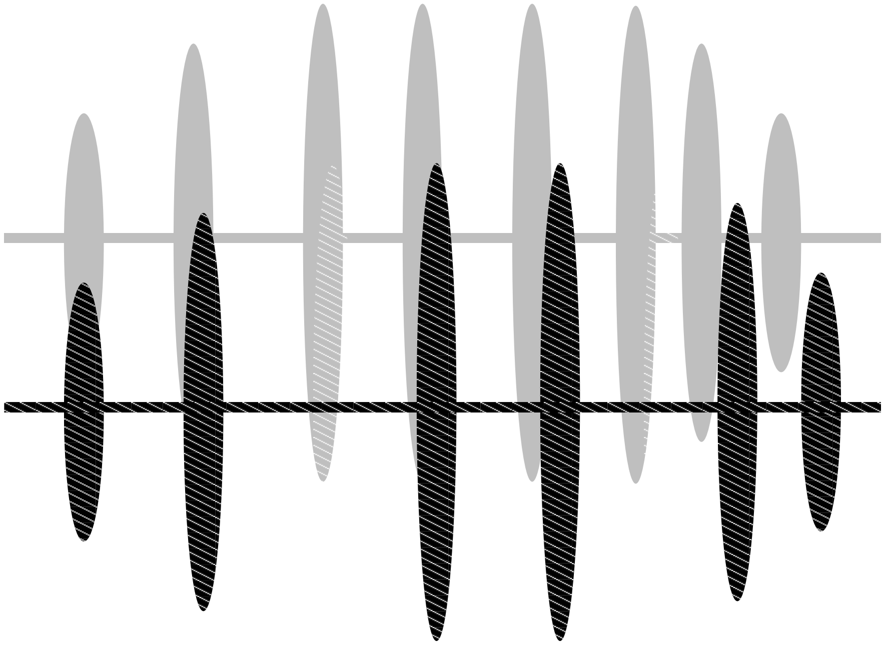
Other proposed mechanisms for the smallness of $m_\nu \sim \frac{m_f}{(V_\delta)^{1/2}}$ in terms of extra compactified dimensions.

Neutrino Oscillations

ν weak eigenstates may be different from ν mass eigenstates.

2 flavours situation, mixing angle θ:

$$\begin{aligned} \nu_e &= \nu_1 \cos\theta + \nu_2 \sin\theta \\ \nu_f &= -\nu_1 \sin\theta + \nu_2 \cos\theta \end{aligned}$$



Weak decay produces distinct weak eigenstate $\nu(0) = \nu_e$, say

$$\nu(t) = \nu_1 e^{-iE_1 t} \cos\theta + \nu_2 e^{-iE_2 t} \sin\theta$$

Ultrarelativistically, $p \sim E - \frac{m^2}{2E}$.

$$P[\nu_e \to \nu_f; L] \quad = \quad \sin^2 2\theta \sin^2 \frac{E_2 - E_1}{2} t.$$

$$\begin{aligned} P[\nu_e \to \nu_f; L] \quad &\simeq \quad \sin^2 2\theta \sin^2 \frac{\delta {m_{21}}^2 L}{4E} \\ &\simeq \quad \sin^2 2\theta \sin^2 \frac{1.27(\delta m_{21}/eV)^2 (L/km)}{E/GeV} \end{aligned}$$

SOLAR NEUTRINOS

ν_e's with sub-MeV to a few MeV energies from the solar core

Main nuclear reactions

Reaction	Max. flux in $m^{-2}s^{-1}$ from SSM	E_ν
$pp \to de^+\nu_e$	$\sim 6 \times 10^{14}$	0 to 0.420 MeV
$pep \to d\nu_e$	$\sim 1.5 \times 10^{12}$	1.8 MeV
$^7B_ee \to \ ^7Li\nu_e$	$\sim 4.75 \times 10^{13}$	0.38 MeV & 0.87 MeV
$^8B \to \ ^8B_e^*e^+\nu_e$	$\sim 5 \times 10^{10}$	0 to 14.6 MeV
$^{13}N \to \ ^{12}Ce^+\nu_e$	$\sim 5.5 \times 10^{12}$	0 to 1.25 MeV
$^{15}O \to \ ^{15}Nle^+\nu_e$	$\sim 4.8 \times 10^{12}$	0 to 1.75 MeV
$^{17}F \to \ ^{17}Oe^+\nu_e$	$\sim 5.5 \times 10^{10}$	0 to 1.75 MeV

Detection (deep underground)

(1) Radiochemical

HOMESTAKE $\nu_e\,^{37}Cl \to e\,^{37}A$ DAVIS

$\downarrow$ Nobel 2002

Atoms counted
using Auger effect.

GALLEX/SAGE $\nu_e\, {}^{71}Ga \to e\, {}^{71}Ge$

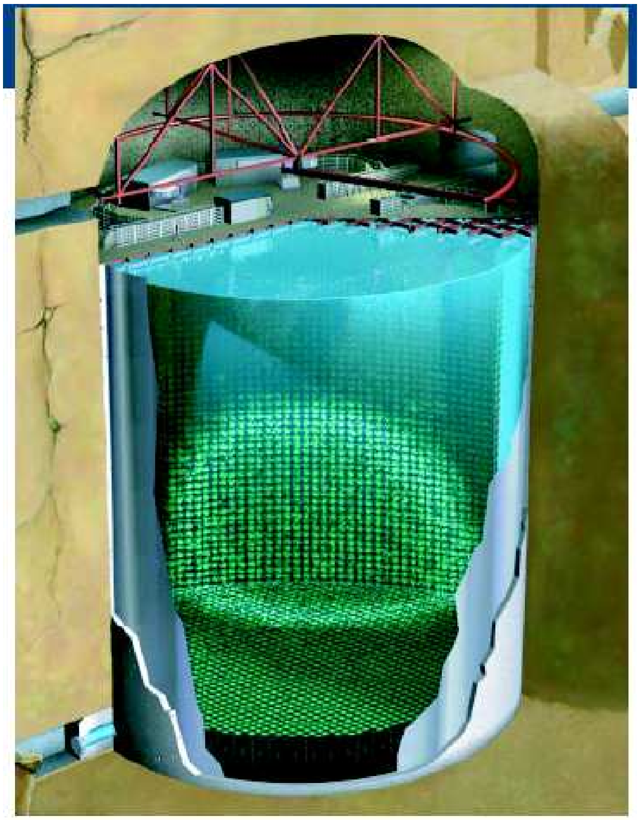
$$\underset{\text{liquid}}{\uparrow} \qquad \underset{\text{gas}}{\uparrow}$$

(2) Realtime scattering in water $\nu_e \to \nu_e e$. KOSHIBA

Works less efficiently Nobel 2002

for ν_μ and ν_τ: $\nu_{\mu,\tau} e \to \nu_{\mu,\tau} e$

Directionality (to Sun) via Cerenkov cones.



(3) Realtime scattering in heavy water D_2O (SNO)

$$\nu_e d \to epp$$
$$\nu_x d \to \nu_x pn$$
$$x = e, \mu, \tau$$

Reduced ν_e fluxes detected as compared to SSM expectations.

Explanation: flavour conversion $\nu_e \longrightarrow \nu_{\mu,\tau}$.

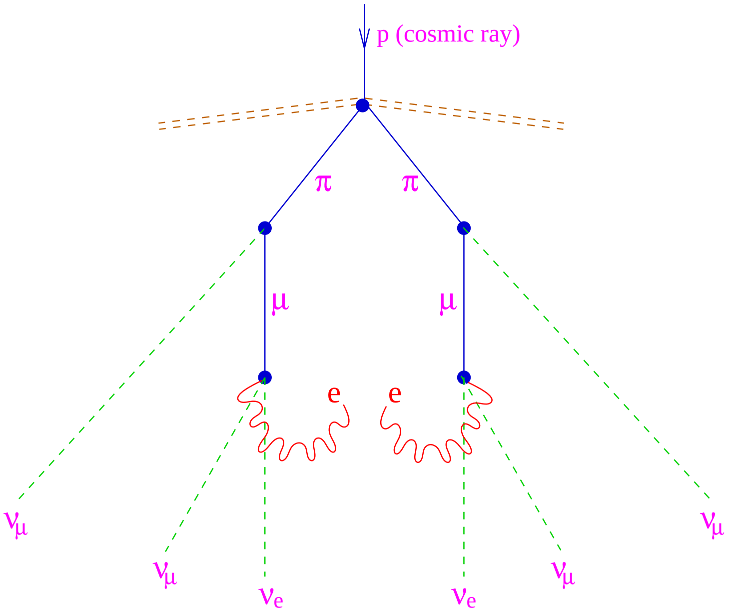
$$\mathrm{SNO} = \frac{\text{observed } \nu_e \text{ flux}}{\text{observed } \nu_x \text{ flux}} = \frac{(\nu_e - \text{flux})_{\text{Earth}}}{(\nu_e - \text{flux})_{\text{Sun}}}$$

$$P_{ee} = 1 - \sin^2 2\theta_\odot \sin^2 \frac{1.27(\delta m^2_{21}/ev^2)(L/km)}{E/GeV}$$

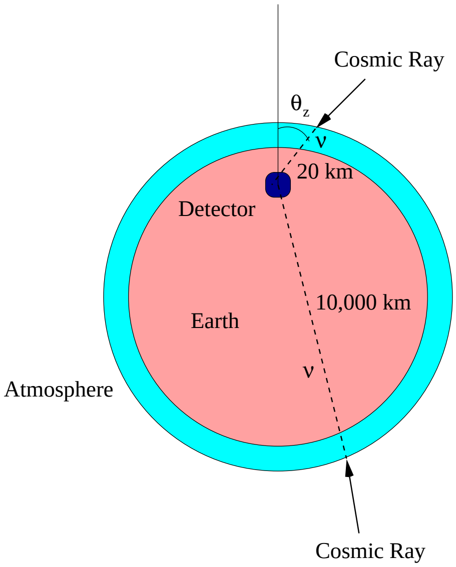
+ Resonant enhancement of flavour conversion in solar medium MSW

$\Longrightarrow \delta m^2_{21} = (6.8 \pm 0.8) \times 10^{-5} eV^2,\ \theta_S = 32.5^\circ \pm 2.5^\circ$.

ATMOSPHERIC NEUTRINOS

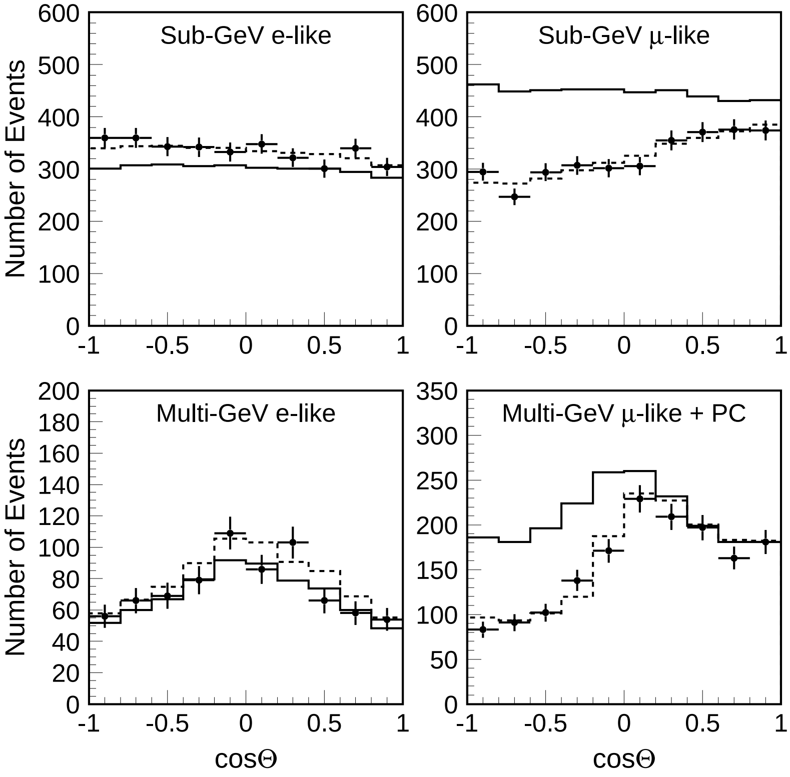


Roughly, expected $\frac{N(\nu_\mu)}{N(\nu_e)} \simeq 2.$ *Seen: almost equal nos.*



sub-GeV: $\frac{(N_\mu/N_e)_{data}}{(N_\mu/N_e)_{expected}} = 0.652 \pm 0.019 \pm 0.051$

multi-GeV μ-like: $\frac{N_\mu^{up} - N_\mu^{down}}{N_\mu^{up} + N_\mu^{down}} = -0.296 \pm 0.032 \pm 0.01$



Best interpretation: $\nu_\mu \leftrightarrow \nu_\tau$ *oscillation*

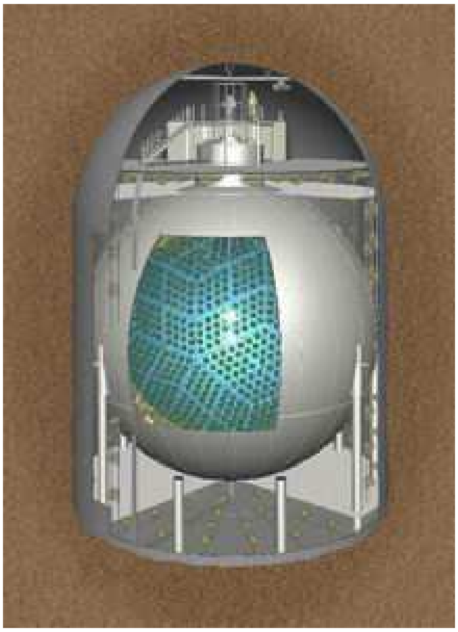
$$|\delta m^2_{32}| = (2.6 \pm 0.4) \times 10^{-3} eV^2$$

$$\theta_A = 45^\circ \pm 5^\circ.$$

Indian initiative: India-based Neutrino Observatory (INO)

Underground calorimetric detector: magnetized iron layers with RPC's.

REACTOR NEUTRINOS



KamLAND expt:

$\bar{\nu}_e$ beams from 50 reactors between 150 and 350 kms into 1 kton liquid scintillator detector at Kamioka. Detection via $\bar{\nu}_e + p \rightarrow e^+ + n$. Measured flux vs. input calculated flux clearly supports δm^2_{21} and $\theta_\odot$ values.

CHOOZ expt:

$\bar{\nu}_e$'s from two cores in a French nuclear power plant.
No depletion found at $L \sim 1 km \Longrightarrow |\theta_{13}| < 13°$.
Double-CHOOZ expt. being undertaken with one more "near" detector at $L \sim$ 100 – 200 m from the cores.
Hopes to improve limit on θ_{13} by factor 3.
New KASKA (Kashiwazaki-Kariwa complex) expt in Japan, Krasnoyarsk in Russia and Daya Bay in China.

COSMOLOGICAL NEUTRINOS

Generated from the Big Bang

$$N(p) = \frac{1}{e^{\frac{p}{kT_c}} + 1}$$

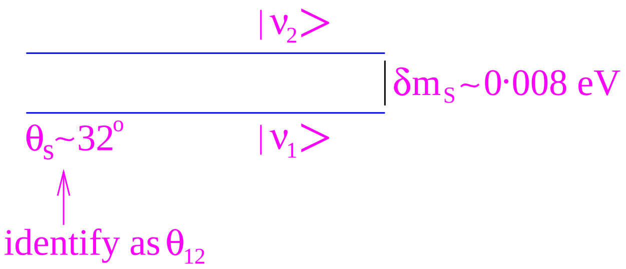
Decoupled about 1 min after BB. HDM today
About 330 $(\nu, \bar{\nu})$'s/cm^3.

$$\begin{aligned} \Omega &= \rho/\rho_c \\ \Omega_{\nu,\bar{\nu}} h^2 &= \frac{\sum_\nu m_\nu}{91.5 eV}, \\ H_0 &= 100\, h\, \mathrm{km\, sec}^{-1} mpc^{-1} \text{ and } h \sim 0.7 \end{aligned}$$

WMAP probe into different components of Ω has bounded Ω_{HDM} from above

$$\Longrightarrow \qquad \sum_\nu m_\nu < 0.71\, eV.$$

NEUTRINO FACTFILE



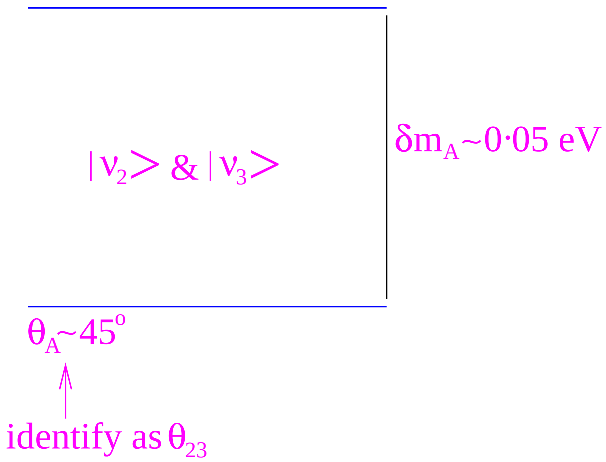
$|\nu_2>$

$\delta m_S \sim 0{\cdot}008$ eV

$|\nu_1>$

$\theta_S \sim 32^o$

identify as θ_{12}



$\delta m_A \sim 0{\cdot}05$ eV

$|\nu_2>$ & $|\nu_3>$

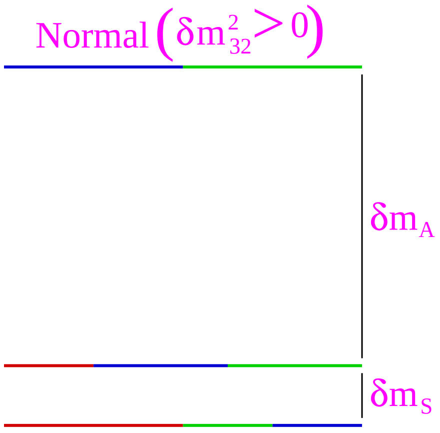
$\theta_A \sim 45^o$

identify as θ_{23}

$$|\theta_{13}| < 13^\circ$$

Two possible types of ordering

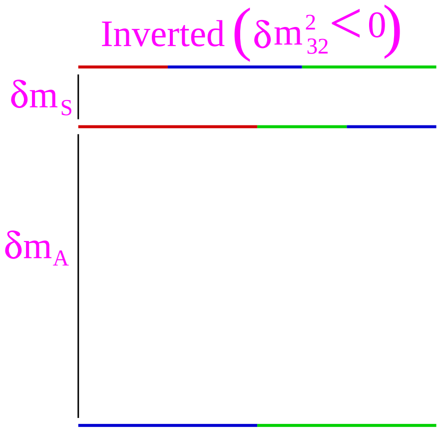
$$\delta m^2_{ij} = m^2_i - m^2_j.$$



Normal $(\delta m^2_{32} > 0)$

δm_A

δm_S



Inverted $(\delta m^2_{32} < 0)$

δm_S

δm_A

LONG BASELINE NEUTRINO STUDIES

- *K2K*
- *T2K*
- *MINOS*
- *CNGS*
  - ↗ *ICARUS*
  - ↘ *OPERA*
- *MINERVA*
- *NOVA*

Accelerator neutrino ($\nu_\mu, \bar{\nu}_\mu$ *or* β*-beams* ν_e, $\bar{\nu}_e$) *beam + near detector + far detector*

Project	Accelerator	Location of far detector	Dist. kms.	$< E_\nu >$ GeV	Status
K2K	KEK p synchrotron	Kamioka mines	250	1.4	Started April '99
Minos	Fermilab Main injector	Soudan mine	730	3 $\pm$ 1	To start in 2005
CNGS	CERN 450 GeV SPS	Gransasso Lab	732	a few GeV	– do –
T2K	p accelerator JHF, Tokai	Kamloka mines	295	$\leq$ 1 GeV	?
Minerva Nova	Fermilab main injector Superberm ?	Soudan 15 km off-axis surface	732+	1 $\simeq$ 2 GeV	?

superbeams
neutrino factories

Our result

B. Brahmachari, S. Choubey & PR: Nucl. Phys. **B671** (2003) 483.

S. Choubey & PR: Phys. Rev. Lett. **93** (2004) 021803.

$|\nu_\alpha\rangle$ = *neutrino flavour states* $(\alpha = e, \mu, \tau)$ *participating in EW gauge interactions.*

$|\nu_i\rangle$ = *neutrino mass eigenstates with masses* $m_i (i, 1, 2, 3)$

$$|\nu_\alpha\rangle = \underset{\substack{\uparrow \\ \text{unitary transformation}}}{U_{\alpha i}} |\nu_i >$$

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

$$\left.\begin{array}{l} |\nu_1\rangle \rightarrow |\nu_e\rangle \\ |\nu_2\rangle \rightarrow |\nu_\mu\rangle \\ |\nu_3\rangle \rightarrow |\nu_\tau\rangle \end{array}\right\} \text{when } U \rightarrow I : \quad \text{PMNS convention}$$

Propagation in vacuum

$$\begin{aligned}|\nu_i\rangle_L &= e^{ip_iL}|\nu_i\rangle_0\\ |\nu_\alpha\rangle_L &= U_{\alpha i}|\nu_i\rangle_L = U_{\alpha i}U^*_{\beta i}e^{ip_iL}|\nu_\beta\rangle_0\\ S_{\alpha\to\beta}(L) &= <\nu_\beta|\nu_\alpha>_0 = U_{\alpha i}U^*_{\beta i}e^{ip_iL}.\\ P[\nu_\alpha(0)\to\nu_\beta(L)] &= |S_{\alpha\to\beta}(L)|^2.\end{aligned}$$

Ultrarelativistically, $p \sim E - \frac{m^2}{2E}$. Define $\Delta_{ij} \equiv \frac{m_i^2 - m_j^2}{4E}L$.

In the approximation $|\delta m_{32}|^2 \gg |\delta m_{21}^2|$ one can show that

$$\begin{aligned}P[\nu_\mu(0)\to\nu_\mu(L)]_{vac} &\simeq 1 - 4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)\sin^2\Delta_{31}\\ &= P[\bar\nu_\mu(0)\to\bar\nu_\mu(L)]_{vac}\end{aligned}$$

ν_μ survival probability in vacuum, minimum for $|U_{\mu 3}| = 1/\sqrt{2}$.

ν_μ flavour conversion probability maximal for $|U_{\mu 3}| = 1/\sqrt{2}$.

$|U_{\mu 3}|$ known to be $\sim 1/\sqrt{2}$.

$|\frac{1}{\sqrt{2}} - |U_{\mu 3}||$ is the deviation from maximality difficult to measure at a minimum.

Propagation in matter

But, through matter (earth mantle) of roughly uniform density, we have a result

$$\begin{aligned}\Delta P_{\mu\mu} &= P[\nu_\mu(0) \to \nu_\mu(L)] - P[\bar{\nu}_\mu(0) \to \bar{\nu}_\mu(L)] \\ &= 4|U_{e3}|^2|U_{\mu 3}|^2(1 - 2|U_{\mu 3}|^2)A[2L\Delta_{31}^{-1}\sin^2\Delta_{31} \\ &\qquad - L\sin(2\Delta_{31})] + O(A^3),\end{aligned}$$

where $A = \sqrt{2}G_F \underset{\uparrow}{N_e}$

Earth electron density

A measurment of this will directly yield the deviation of muon neutrino mixing from maximality. Feasible in the Fermilab–Soudan setup.

CONCLUDING REMARKS

A glimpse of the world of neutrinos.
Only indication of new physics beyond the Standard Model.

Not covered

- *Geothermal neutrinos*
- *Neutrino astronomy*
- *CP violation in neutrino sector*