Phenomenological Status of Neutrino Mixing

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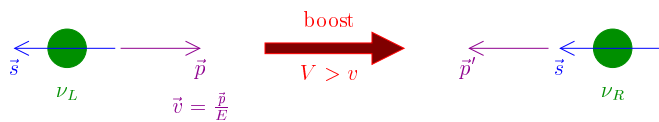mailto://giunti@to.infn.it

Neutrino Unbound: http://www.nu.to.infn.it

SIF, XCIII Congresso Nazionale, Pisa, 25 Settembre 2007

Outline

Standard Model: Massless Neutrinos

Standard Model: $\nu_L, \nu_L^c = (\nu^c)_R \implies$ no Dirac mass term

$$\mathcal{L}^D \sim m^D \overline{\nu_L} \nu_R \qquad (\text{no } \nu_R, (\nu^c)_L)$$

Majorana Neutrino: $\nu \equiv \nu^c$

$$(\nu^c)_R \equiv \nu_R \implies \text{Majorana mass term}$$

$$\mathcal{L}^M \sim m^M \overline{\nu_L} \nu_L^c = m^M \overline{\nu_L}(\nu^c)_R$$

Standard Model: Majorana mass term not allowed by $SU(2)_L \times U(1)_Y$

(no Higgs triplet)

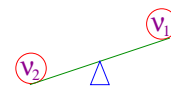
Extension of the SM: Massive Neutrinos

Standard Model can be extended with ν_R (e_L, e_R; u_L, u_R; d_L, d_R; ...)

$\nu_L + \nu_R \Rightarrow$ Dirac neutrino mass term $\mathcal{L}^D \sim m^D \overline{\nu_L} \nu_R \Rightarrow m^D \lesssim 100 \, \text{GeV}$

surprise: Majorana neutrino mass for ν_R is allowed! $\quad \mathcal{L}^M_R \sim m^M_R \overline{(\nu^c)_L} \nu_R$

total neutrino mass term $\quad \mathcal{L}^{D+M} \sim \begin{pmatrix} \overline{\nu_L} & \overline{(\nu^c)_L} \end{pmatrix} \begin{pmatrix} 0 & m^D \\ m^D & m^M_R \end{pmatrix} \begin{pmatrix} (\nu^c)_R \\ \nu_R \end{pmatrix}$

m^M_R can be arbitrarily large (not protected by SM symmetries)

$m^M_R \sim$ scale of new physics beyond Standard Model $\Rightarrow m^M_R \gg m^D$

diagonalization of $\begin{pmatrix} 0 & m^D \\ m^D & m^M_R \end{pmatrix} \quad \Rightarrow \quad m_1 \simeq \dfrac{(m^D)^2}{m^M_R}, \quad m_2 \simeq m^M_R$

natural explanation of
smallness of neutrino masses

massive neutrinos are Majorana!

see-saw mechanism

[Minkowski, PLB 67 (1977) 42]

[Yanagida (1979); Gell-Mann, Ramond, Slansky (1979); Mohapatra, Senjanovic, PRL 44 (1980) 912]

Lepton Numbers

Standard Model: Lepton numbers are conserved

	L_e	L_μ	L_τ
(ν_e, e^-)	$+1$	0	0
(ν_μ, μ^-)	0	$+1$	0
(ν_τ, τ^-)	0	0	$+1$

	L_e	L_μ	L_τ
$((\nu^c)_e, e^+)$	-1	0	0
$((\nu^c)_\mu, \mu^+)$	0	-1	0
$((\nu^c)_\tau, \tau^+)$	0	0	-1

$$L = L_e + L_\mu + L_\tau$$

Dirac mass term $m^D \overline{\nu_L} \nu_R \rightarrow \begin{pmatrix} \overline{\nu_{eL}} & \overline{\nu_{\mu L}} & \overline{\nu_{\tau L}} \end{pmatrix} \begin{pmatrix} m^D_{ee} & m^D_{e\mu} & m^D_{e\tau} \\ m^D_{\mu e} & m^D_{\mu\mu} & m^D_{\mu\tau} \\ m^D_{\tau e} & m^D_{\tau\mu} & m^D_{\tau\tau} \end{pmatrix} \begin{pmatrix} \nu_{eR} \\ \nu_{\mu R} \\ \nu_{\tau R} \end{pmatrix}$

L_e, L_μ, L_τ are not conserved, but L is conserved $L(\nu_{\alpha R}) = L(\nu_{\beta L}) \Rightarrow |\Delta L| = 0$
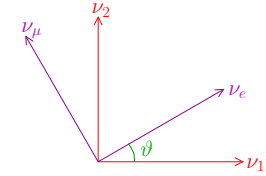
Majorana mass term $m^M \overline{\nu_L}(\nu^c)_R \rightarrow \begin{pmatrix} \overline{\nu_{eL}} & \overline{\nu_{\mu L}} & \overline{\nu_{\tau L}} \end{pmatrix} \begin{pmatrix} m^M_{ee} & m^M_{e\mu} & m^M_{e\tau} \\ m^M_{\mu e} & m^M_{\mu\mu} & m^M_{\mu\tau} \\ m^M_{\tau e} & m^M_{\tau\mu} & m^M_{\tau\tau} \end{pmatrix} \begin{pmatrix} (\nu^c_e)_R \\ (\nu^c_\mu)_R \\ (\nu^c_\tau)_R \end{pmatrix}$

L, L_e, L_μ, L_τ are not conserved $L(\nu^c_\alpha) = -L(\nu_\beta) \Rightarrow |\Delta L| = 2$

Two-Neutrino Mixing and Oscillations

$$|\nu_\alpha\rangle = \sum_{k=1}^{2} U_{\alpha k} |\nu_k\rangle \qquad (\alpha = e, \mu)$$

$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

$|\nu_e\rangle = \cos\vartheta |\nu_1\rangle + \sin\vartheta |\nu_2\rangle$
$|\nu_\mu\rangle = -\sin\vartheta |\nu_1\rangle + \cos\vartheta |\nu_2\rangle$
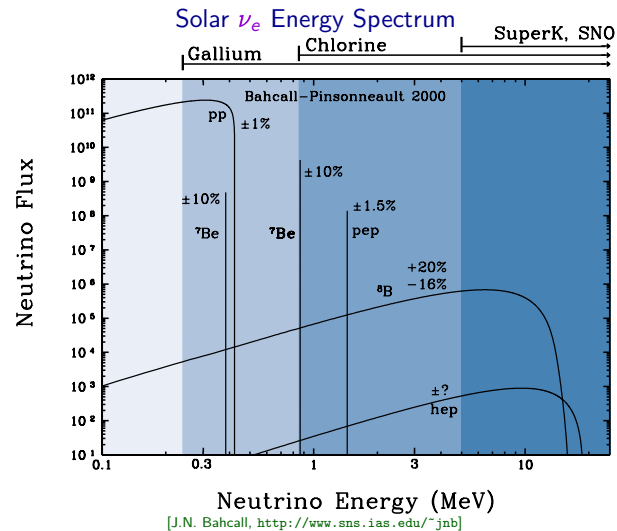
$$\Delta m^2 \equiv \Delta m^2_{21} \equiv m^2_2 - m^2_1$$

Transition Probability: $P_{\nu_e \rightarrow \nu_\mu} = P_{\nu_\mu \rightarrow \nu_e} = \sin^2 2\vartheta \sin^2 \left(\dfrac{\Delta m^2 L}{4E} \right)$

Survival Probabilities: $P_{\nu_e \rightarrow \nu_e} = P_{\nu_\mu \rightarrow \nu_\mu} = 1 - P_{\nu_e \rightarrow \nu_\mu}$

Solar Neutrinos

Solar ν_e Energy Spectrum

[J.N. Bahcall, http://www.sns.ias.edu/~jnb]

Homestake+Kam.+GALLEX+SAGE+Super-K+SNO

$\Phi^{SNO}_{\nu_e} = 1.76 \pm 0.11 \times 10^6 \, \text{cm}^{-2} \, \text{s}^{-1}$

$\Phi^{SNO}_{\nu_e, \nu_\mu, \nu_\tau} = 5.09 \pm 0.66 \times 10^6 \, \text{cm}^{-2} \, \text{s}^{-1}$

SNO solved
solar neutrino problem
$\Downarrow$
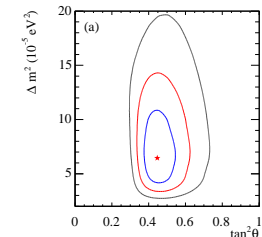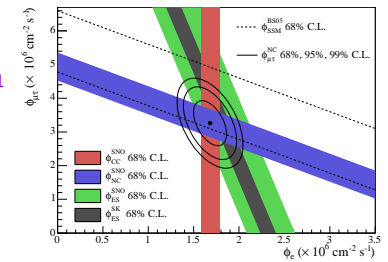Neutrino Physics
(April 2002)

[SNO, PRL 89 (2002) 011301, nucl-ex/0204008]

$\nu_e \rightarrow \nu_\mu, \nu_\tau$ oscillations
$\Downarrow$
LMA: Large Mixing Angle solution

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

$\tan^2 \vartheta \simeq 0.45^{+0.09}_{-0.08}$
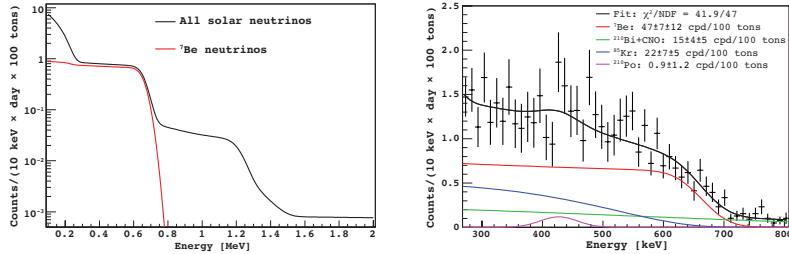

[SNO, PRC 72 (2005) 055502, nucl-ex/0502021]

BOREXino

Real-time measurement of ^{7}Be solar neutrinos ($0.862\,\text{MeV}$)

$\nu + e \to \nu + e$ $E = 0.862\,\text{MeV}$ $\implies$ $\sigma_{\nu_e} \simeq 5.5\,\sigma_{\nu_\mu,\nu_\tau}$

$n_{\text{the}}^{\text{no-osc}} = 75 \pm 4\,\text{day}^{-1}\,(100\,\text{tons})^{-1}$ $n_{\text{exp}} = 47 \pm 7 \pm 12\,\text{day}^{-1}\,(100\,\text{tons})^{-1}$

$n_{\text{the}}^{\text{osc}} = 49 \pm 4\,\text{day}^{-1}\,(100\,\text{tons})^{-1}$ $(n_{\text{the}}^{\text{no-osc}} - n_{\text{exp}})/\Delta n \simeq 1.9$

KamLAND

Reactor $\bar{\nu}_e \to \bar{\nu}_e$ confirmation of LMA (December 2002)
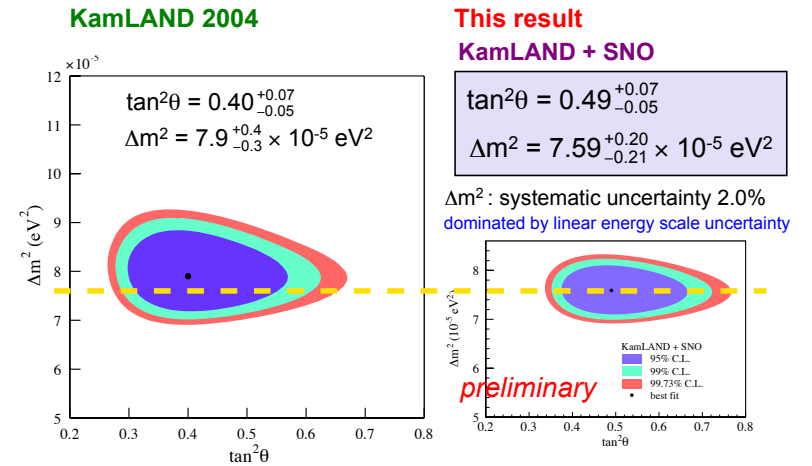
53 nuclear power reactors in Japan and Korea $\to$ Kamioka Mine

$\langle L \rangle \simeq 180\,\text{km}$ $\langle E \rangle \simeq 4\,\text{MeV}$

short baseline experiment

preliminary

hypothetical single reactor at 180 km

small matter effect

SNO   KamLAND

KamLAND only

$\tan^2\theta = 0.56^{+0.14}_{-0.09}$

$\Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5}\,\text{eV}^2$

(marginalized error)

3 neutrino effect

> 6σ LMA II

preliminary

> 4σ

LMA 0

preliminary

same result for Δm^2

KamLAND 2004

$\tan^2\theta = 0.40^{+0.07}_{-0.05}$

$\Delta m^2 = 7.9^{+0.4}_{-0.3} \times 10^{-5}\,\text{eV}^2$

This result

KamLAND + SNO

$\tan^2\theta = 0.49^{+0.07}_{-0.05}$

$\Delta m^2 = 7.59^{+0.20}_{-0.21} \times 10^{-5}\,\text{eV}^2$

Δm^2 : systematic uncertainty 2.0%
dominated by linear energy scale uncertainty

preliminary

Δm^2 is measured at 2.8% precision by KamLAND

Atmospheric Neutrinos

$$\frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \simeq 2 \quad \text{at } E \lesssim 1\,\text{GeV}$$

uncertainty on ratios: $\sim 5\%$

uncertainty on fluxes: $\sim 30\%$

ratio of ratios

$$R \equiv \frac{[N(\nu_\mu + \bar{\nu}_\mu)/N(\nu_e + \bar{\nu}_e)]_{\text{data}}}{[N(\nu_\mu + \bar{\nu}_\mu)/N(\nu_e + \bar{\nu}_e)]_{\text{MC}}}$$

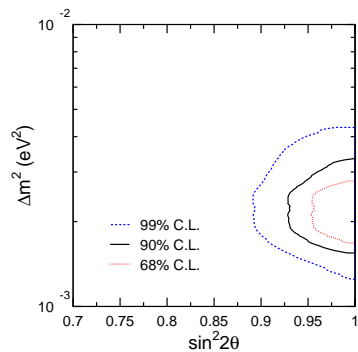$$R^{\text{K}}_{\text{sub-GeV}} = 0.60 \pm 0.07 \pm 0.05$$

[Kamiokande, PLB 280 (1992) 146]

$$R^{\text{K}}_{\text{multi-GeV}} = 0.57 \pm 0.08 \pm 0.07$$

[Kamiokande, PLB 335 (1994) 237]

Super-Kamiokande Up-Down Asymmetry

$E_\nu \gtrsim 1\,\text{GeV} \Rightarrow$ isotropic flux of cosmic rays

$$\phi^{(A)}_{\nu_\alpha}(\theta^{AB}_z) = \phi^{(B)}_{\nu_\alpha}(\pi - \theta^{AB}_z) \quad \phi^{(A)}_{\nu_\alpha}(\theta^{AB}_z) = \phi^{(B)}_{\nu_\alpha}(\theta^{AB}_z)$$
$$\Downarrow$$
$$\phi^{(A)}_{\nu_\alpha}(\theta_z) = \phi^{(A)}_{\nu_\alpha}(\pi - \theta_z)$$

(December 1998)

$$A^{\text{up-down}}_{\nu_\mu}(\text{SK}) = \left(\frac{N^{\text{up}}_{\nu_\mu} - N^{\text{down}}_{\nu_\mu}}{N^{\text{up}}_{\nu_\mu} + N^{\text{down}}_{\nu_\mu}} \right) = -0.296 \pm 0.048 \pm 0.01$$

[Super-Kamiokande, Phys. Rev. Lett. 81 (1998) 1562, hep-ex/9807003]

6σ MODEL INDEPENDENT EVIDENCE OF ν_μ DISAPPEARANCE!

Fit of Super-Kamiokande Atmospheric Data

Measure of ν_τ CC Int. is Difficult:

▶ $E_{\text{th}} = 3.5\,\text{GeV} \Longrightarrow \sim 20\,\text{events/yr}$

▶ τ-Decay $\Longrightarrow$ Many Final States

ν_τ-Enriched Sample

$$N^{\text{the}}_{\nu_\tau} = 78 \pm 26 \ @ \ \Delta m^2 = 2.4 \times 10^{-3}\,\text{eV}^2$$

$$N^{\text{exp}}_{\nu_\tau} = 138^{+50}_{-58}$$

$$N_{\nu_\tau} > 0 \quad @ \quad 2.4\sigma$$

[Super-Kamiokande, PRL 97(2006) 171801, hep-ex/0607059]

$$\nu_\mu \to \nu_\tau$$

Best Fit: $\begin{cases} \Delta m^2 = 2.1 \times 10^{-3}\,\text{eV}^2 \\ \sin^2 2\theta = 1.0 \end{cases}$

1489.2 live-days (Apr 1996 – Jul 2001)

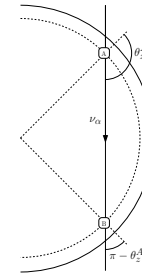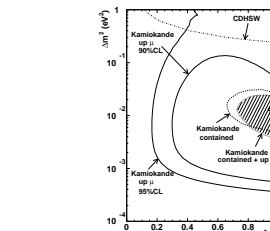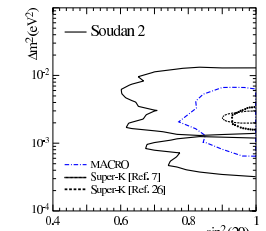[Super-Kamiokande, PRD 71 (2005) 112005, hep-ex/0501064]

Future Check: OPERA ($\nu_\mu \to \nu_\tau$)
CERN to Gran Sasso (CNGS)
$L \simeq 732\,\text{km} \quad \langle E \rangle \simeq 18\,\text{GeV}$
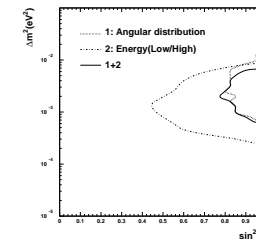
[NJP 8 (2006) 303, hep-ex/0611023]
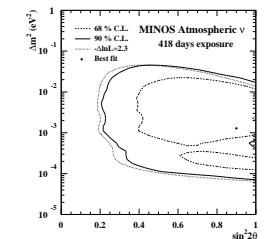
Kamiokande, Soudan-2, MACRO and MINOS

[Kamiokande, PRL 81 (1998) 2016, hep-ex/9806038]

[Soudan 2, PRD 72 (2005) 052005, hep-ex/0507068]

[MACRO, PLB 566 (2003) 35, hep-ex/0304037]

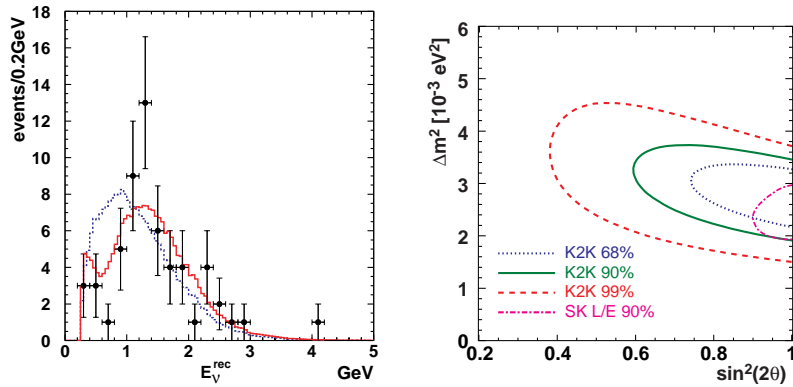[MINOS, PRD 73 (2006) 072002, hep-ex/0512036]

K2K

KEK to Kamioka (Super-Kamiokande) $\nu_\mu \to \nu_\mu$

$L \simeq 250\,\text{km}$ $\langle E \rangle \simeq 1.3\,\text{GeV}$

confirmation of atmospheric allowed region (June 2002)

- K2K 68%
- K2K 90%
- K2K 99%
- SK L/E 90%

best fit: $\Delta m^2 = 2.75 \times 10^{-3}\,\text{eV}$ $\sin^2 2\vartheta = 1.00$

[K2K, PRD 74 (2006) 072003, hep-ex/0606032]

MINOS

Fermilab to Soudan Mine (Minnesota) $\nu_\mu \to \nu_\mu$

$L \simeq 730\,\text{km}$ $\langle E \rangle \simeq 3.5\,\text{GeV}$

[MINOS, TAUP 2007]

Experimental Evidences of Neutrino Oscillations

Solar
$\nu_e \to \nu_\mu, \nu_\tau$

- Homestake
- Kamiokande/Super-K
- GALLEX/GNO
- SAGE
- Super-Kamiokande
- SNO
- BOREXino

Reactor
$\bar{\nu}_e$ disappearance

(KamLAND)

$\xrightarrow{2\sigma}$

$\Delta m^2_{\text{SUN}} = 7.59\,(1 \pm 0.03) \times 10^{-5}\,\text{eV}^2$

$\sin^2 \vartheta_{\text{SUN}} = 0.49\left(1^{+0.14}_{-0.10}\right)$

[I. Shimizu (KamLAND), TAUP 2007]

Atmospheric
$\nu_\mu \to \nu_\tau$

- Kamiokande
- IMB
- Super-Kamiokande
- MACRO
- Soudan-2

Accelerator
ν_μ disappearance

(K2K & MINOS)

$\xrightarrow{2\sigma}$

$\Delta m^2_{\text{ATM}} = 2.6\left(1^{+0.14}_{-0.15}\right) \times 10^{-3}\,\text{eV}^2$

$\sin^2 \vartheta_{\text{ATM}} = 0.45\left(1^{+0.35}_{-0.20}\right)$

[Fogli et al, PRD 75 (2007) 053001, hep-ph/0608060]

Three-Neutrino Mixing

$$\nu_{\alpha L} = \sum_{k=1}^{3} U_{\alpha k}\, \nu_{kL} \qquad (\alpha = e, \mu, \tau)$$

three flavor fields ν_e, ν_μ, ν_τ
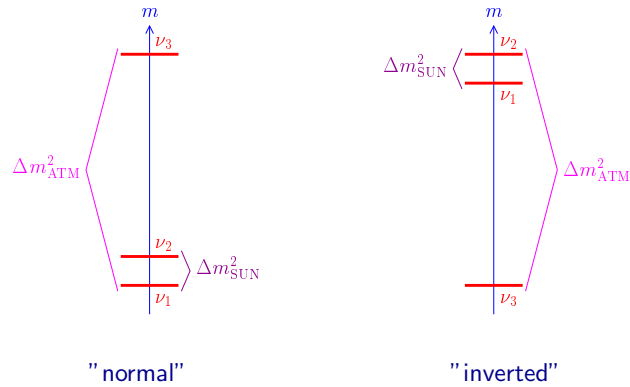
three massive fields ν_1, ν_2, ν_3

$$\Delta m^2_{\text{SUN}} = \Delta m^2_{21} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$$

$$\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq 2.5 \times 10^{-3}\,\text{eV}^2$$

Allowed Three-Neutrino Schemes

"normal"   "inverted"

different signs of $\Delta m^2_{31} \simeq \Delta m^2_{32}$

absolute scale is not determined by neutrino oscillation data

Mixing Matrix

$$\Delta m^2_{21} \ll |\Delta m^2_{31}|$$

CHOOZ: $\begin{cases} \Delta m^2_{\text{CHOOZ}} = \Delta m^2_{31} = \Delta m^2_{\text{ATM}} \\ \sin^2 2\vartheta_{\text{CHOOZ}} = 4|U_{e3}|^2(1 - |U_{e3}|^2) \end{cases}$

$\Downarrow$

$$|U_{e3}|^2 \lesssim 5 \times 10^{-2} \text{ for } \Delta m^2 \gtrsim 2 \times 10^{-2} \text{ eV}^2$$

SOLAR AND ATMOSPHERIC ν OSCILLATIONS
ARE PRACTICALLY DECOUPLED!

[CHOOZ, PLB 466 (1999) 415]

see also [Palo Verde, PRD 64 (2001) 112001]

TWO-NEUTRINO SOLAR and ATMOSPHERIC ν OSCILLATIONS ARE OK!

$\sin^2 \vartheta_{\text{SUN}} = \dfrac{|U_{e2}|^2}{1 - |U_{e3}|^2} \simeq |U_{e2}|^2 \quad \sin^2 \vartheta_{\text{ATM}} = |U_{\mu3}|^2$

[Bilenky, C.G, PLB 444 (1998) 379]

[Guo, Xing, PRD 67 (2003) 053002]

Standard Parameterization of Mixing Matrix

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$
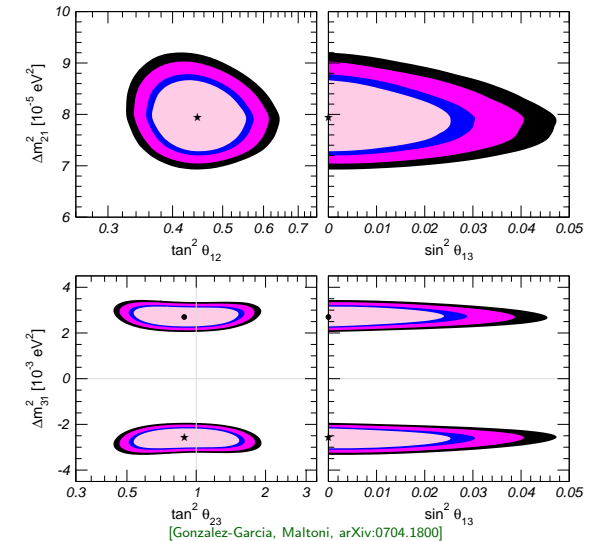
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

$\quad\quad\quad \vartheta_{23} \simeq \vartheta_{\text{ATM}} \quad\quad\quad\quad \vartheta_{13} = \vartheta_{\text{CHOOZ}} \quad\quad\quad\quad \vartheta_{12} \simeq \vartheta_{\text{SUN}} \quad\quad\quad \beta\beta_{0\nu}$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

Global Fit of Oscillation Data: Bilarge Mixing

[Gonzalez-Garcia, Maltoni, arXiv:0704.1800]

$$\Delta m_{21}^2 = 7.9\,^{+0.27}_{-0.28}\left(^{+1.1}_{-0.89}\right)\times 10^{-5}\,\text{eV}^2$$

$$\left|\Delta m_{31}^2\right| = 2.6 \pm 0.2\,(0.6)\times 10^{-3}\,\text{eV}^2$$

$$\theta_{12} = 33.7 \pm 1.3\,\left(^{+4.3}_{-3.5}\right)$$

$$\theta_{23} = 43.3\,^{+4.3}_{-3.8}\,\left(^{+9.8}_{-8.8}\right)$$

$$\theta_{13} = 0\,^{+5.2}_{-0.0}\,\left(^{+11.5}_{-0.0}\right)$$

$$|U|_{90\%} = \begin{pmatrix} 0.81-0.85 & 0.53-0.58 & 0.00-0.12 \\ 0.32-0.49 & 0.52-0.69 & 0.60-0.76 \\ 0.27-0.46 & 0.47-0.64 & 0.65-0.80 \end{pmatrix}$$

$$|U|_{3\sigma} = \begin{pmatrix} 0.79-0.86 & 0.50-0.61 & 0.00-0.20 \\ 0.25-0.53 & 0.47-0.73 & 0.56-0.79 \\ 0.21-0.51 & 0.42-0.69 & 0.61-0.83 \end{pmatrix}$$

[Gonzalez-Garcia, Maltoni, arXiv:0704.1800]

future: measure $\vartheta_{13} \neq 0 \implies$ CP violation, matter effects, mass hierarchy

Absolute Scale of Neutrino Masses

normal scheme

inverted scheme

$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_{\text{SUN}}^2$$
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_{\text{ATM}}^2$$

$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_{\text{ATM}}^2$$
$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_{\text{ATM}}^2$$

Quasi-Degenerate for $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gg \sqrt{\Delta m_{\text{ATM}}^2} \simeq 5 \times 10^{-2}\,\text{eV}$
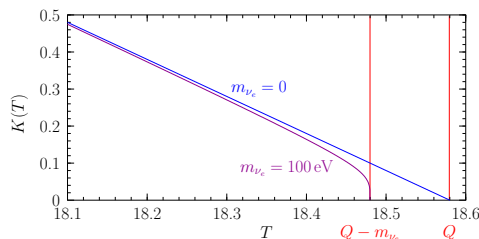
Tritium Beta-Decay

$${}^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e$$

$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C\,G_F)^2}{2\pi^3}\,|\mathcal{M}|^2\,F(E)\,pE\,(Q-T)\sqrt{(Q-T)^2 - m_{\nu_e}^2}$$

$$Q = M_{{}^3\text{H}} - M_{{}^3\text{He}} - m_e = 18.58\,\text{keV}$$

$$m_{\nu_e}^2 = m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2$$

Kurie plot

$$K(T) = \sqrt{\frac{d\Gamma/dT}{\dfrac{(\cos\vartheta_C\,G_F)^2}{2\pi^3}\,|\mathcal{M}|^2\,F(E)\,pE}} = \left[(Q-T)\sqrt{(Q-T)^2 - m_{\nu_e}^2}\right]^{1/2}$$

$$m_{\nu_e} < 2.2\,\text{eV} \quad (95\%\ \text{C.L.})$$
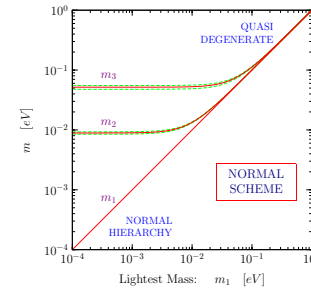
Mainz & Troitsk

[Weinheimer, hep-ex/0210050]

future: KATRIN (start 2010)
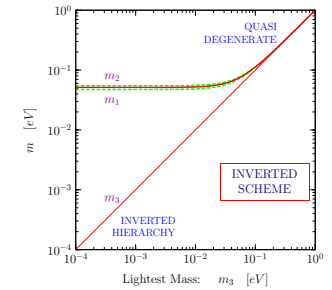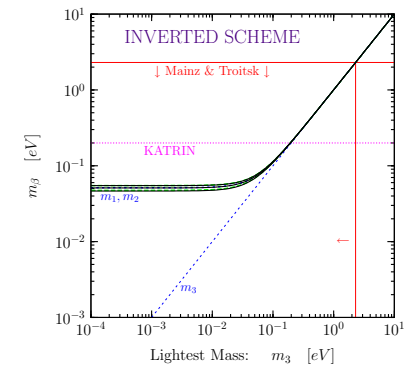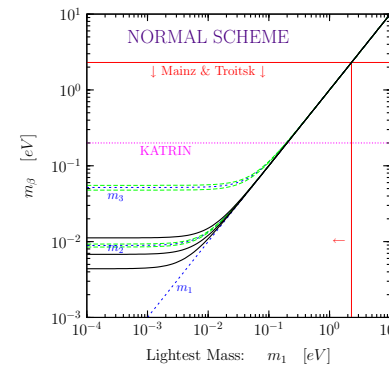
[hep-ex/0109033]   [hep-ex/0309007]

sensitivity: $m_{\nu_e} \simeq 0.2\,\text{eV}$

$$m_{\nu_e}^2 = m_\beta^2 = |U_{e1}|^2\,m_1^2 + |U_{e2}|^2\,m_2^2 + |U_{e3}|^2\,m_3^2$$
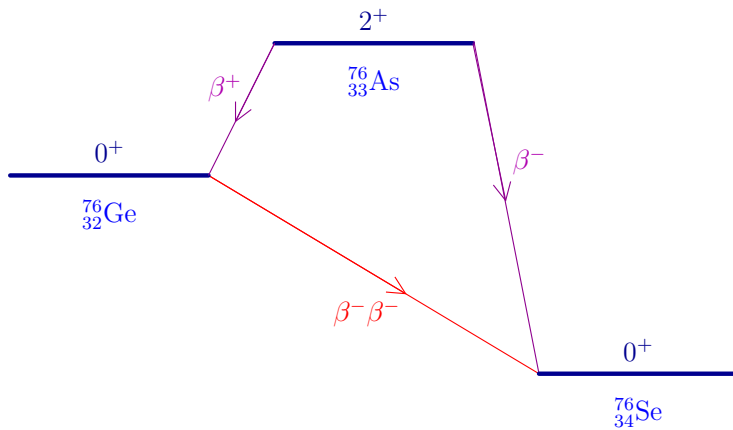

Quasi-Degenerate: $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \implies m_\beta^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2$

FUTURE: IF $m_\beta \lesssim 4\times 10^{-2}\,\text{eV} \implies$ NORMAL HIERARCHY

Neutrinoless Double-Beta Decay

2^+

$^{76}_{33}\text{As}$

β^+

0^+

$^{76}_{32}\text{Ge}$

$\beta^- \beta^-$

β^-

0^+

$^{76}_{34}\text{Se}$

$\mathcal{N}(A, Z) \to \mathcal{N}(A, Z + 2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$

$$\left(T^{2\nu}_{1/2}\right)^{-1} = G_{2\nu} \, |\mathcal{M}_{2\nu}|^2$$

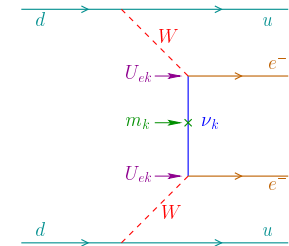second order weak interaction process
in the Standard Model

Neutrinoless Double-β Decay: $\Delta L = 2$

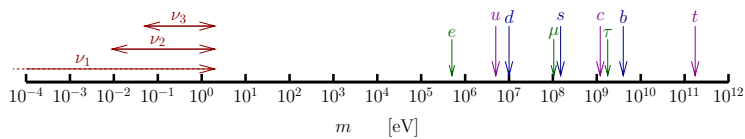$\mathcal{N}(A, Z) \to \mathcal{N}(A, Z + 2) + e^- + e^-$

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu} \, |\mathcal{M}_{0\nu}|^2 \, |m_{\beta\beta}|^2$$

effective
Majorana $m_{\beta\beta} = \sum_k U^2_{ek} \, m_k$
mass

Majorana Neutrino Mass?

ν_3

ν_2

ν_1

$u \, d$ s $c \, b$ t

e μ τ

10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12}

m [eV]

known natural explanation of smallness of ν masses

New High Energy Scale $\mathcal{M}$ $\Rightarrow$ $\begin{cases} \text{See-Saw Mechanism (if } \nu_R\text{'s exist)} \\ \text{5-D Non-Renormaliz. Eff. Operator} \end{cases}$

both imply $\begin{cases} \text{Majorana } \nu \text{ masses} \iff |\Delta L| = 2 \iff \beta\beta_{0\nu} \text{ decay} \\ \text{see-saw type relation } m_\nu \sim \dfrac{\mathcal{M}^2_{\text{EW}}}{\mathcal{M}} \end{cases}$

Majorana neutrino masses provide the most accessible
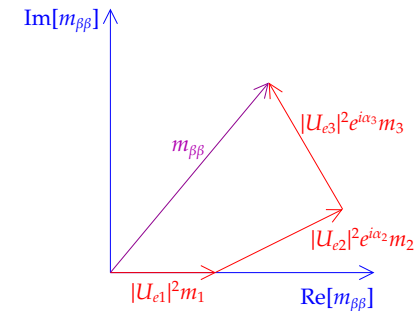window on New Physics Beyond the Standard Model

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Effective Majorana Neutrino Mass

$$m_{\beta\beta} = \sum_k U^2_{ek} \, m_k \qquad \text{complex } U_{ek} \Rightarrow \text{ possible cancellations}$$

$$m_{\beta\beta} = |U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, e^{i\alpha_2} \, m_2 + |U_{e3}|^2 \, e^{i\alpha_3} \, m_3$$

$$\alpha_2 = 2\lambda_2 \qquad \alpha_3 = 2\,(\lambda_3 - \delta_{13})$$

$\text{Im}[m_{\beta\beta}]$

$m_{\beta\beta}$

$|U_{e3}|^2 e^{i\alpha_3} m_3$

$|U_{e2}|^2 e^{i\alpha_2} m_2$

$|U_{e1}|^2 m_1$

$\text{Re}[m_{\beta\beta}]$

Experimental Bounds

Heidelberg-Moscow (^{76}Ge) [EPJA 12 (2001) 147]

$T^{0\nu}_{1/2} > 1.9 \times 10^{25}\,\mathrm{y}$ (90% C.L.) $\implies$ $|m_{\beta\beta}| \lesssim 0.32 - 1.0\,\mathrm{eV}$

IGEX (^{76}Ge) [PRD 65 (2002) 092007]

$T^{0\nu}_{1/2} > 1.57 \times 10^{25}\,\mathrm{y}$ (90% C.L.) $\implies$ $|m_{\beta\beta}| \lesssim 0.33 - 1.35\,\mathrm{eV}$

CUORICINO (^{130}Te) [PRL 95 (2005) 142501]

$T^{0\nu}_{1/2} > 1.8 \times 10^{24}\,\mathrm{y}$ (90% C.L.) $\implies$ $|m_{\beta\beta}| \lesssim 0.2 - 1.1\,\mathrm{eV}$

NEMO 3 (^{100}Mo) [PRL 95 (2005) 182302]

$T^{0\nu}_{1/2} > 4.6 \times 10^{23}\,\mathrm{y}$ (90% C.L.) $\implies$ $|m_{\beta\beta}| \lesssim 0.7 - 2.8\,\mathrm{eV}$

FUTURE EXPERIMENTS
CAMEO, CANDLES, COBRA, EXO, Majorana, XMASS
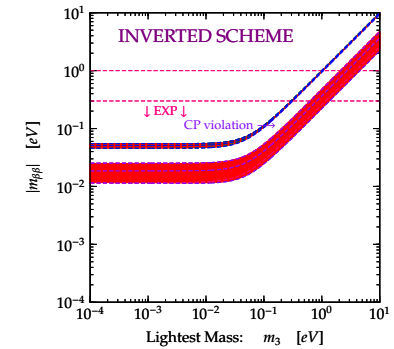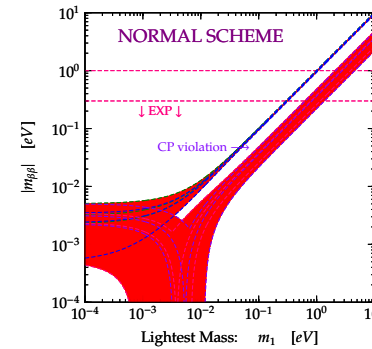$|m_{\beta\beta}| \sim$ few $10^{-1}\,\mathrm{eV}$
CUORE, MOON, GEM, GERDA, SNO++, Super-NEMO
$|m_{\beta\beta}| \sim$ few $10^{-2}\,\mathrm{eV}$

Bounds from Neutrino Oscillations

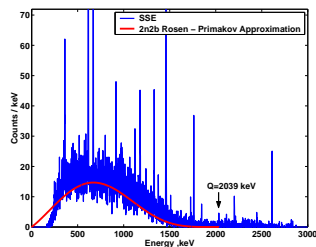$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3$$

FUTURE: IF $|m_{\beta\beta}| \lesssim 10^{-2}\,\mathrm{eV}$ $\implies$ NORMAL HIERARCHY

Experimental Positive Indication

[Klapdor et al., MPLA 16 (2001) 2409]

$T^{0\nu}_{1/2} = (2.23^{+0.44}_{-0.31}) \times 10^{25}\,\mathrm{y}$ 6.5σ evidence   [MPLA 21 (2006) 1547]

[PLB 586 (2004) 198]

[MPLA 21 (2006) 1547]

the indication must be checked by other experiments

$|m_{\beta\beta}| = 0.32 \pm 0.03\,\mathrm{eV}$ [MPLA 21 (2006) 1547]

if confirmed, very exciting (Majorana ν and large mass scale)

Cosmology

H_0 (Hubble Space Telescope Key Project)

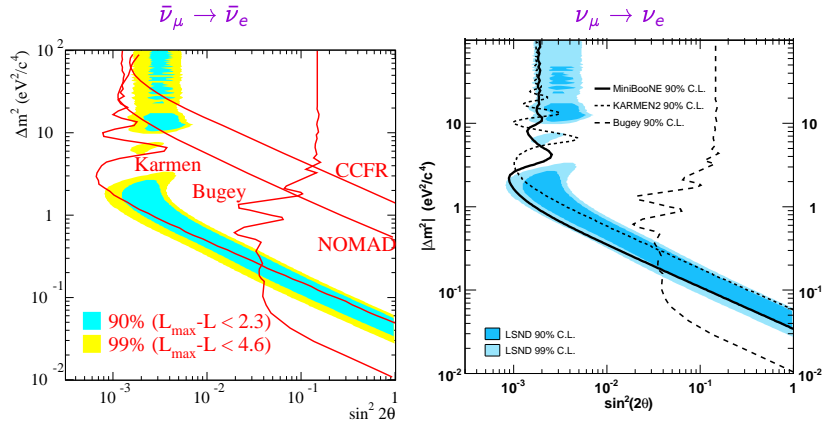CMBR (COBE, WMAP, Boomerang, DASI, MAXIMA, VSA, CBI, ACBAR)

LSS (2dFGRS, SDSS)

SNIa (High-z SN Search Team, Supernova Cosmology Project)

ΛCDM $\implies$ $\sum_{k=1}^{3} m_k \lesssim 0.2 - 0.7\,\mathrm{eV}$

LSND and MiniBooNE

$$\bar{\nu}_\mu \to \bar{\nu}_e$$

$$\nu_\mu \to \nu_e$$

90% (L_{max}-L < 2.3)
99% (L_{max}-L < 4.6)

[LSND, PRD 64 (2001) 112007, hep-ex/0104049]

[MiniBooNE, PRL 98 (2007) 231801, arXiv:0704.1500]

$$\Delta m^2_{LSND} \gtrsim 0.1 \, \text{eV}^2$$

$$\Delta m^2_{LSND} \gg \Delta m^2_{ATM} \gg \Delta m^2_{SUN}$$

$\bar{\nu}_\mu \to \bar{\nu}_e$ is running

MiniBooNE Low-Energy Anomaly

[MiniBooNE, PRL 98 (2007) 231801, arXiv:0704.1500]

Conclusions

$\nu_e \to \nu_\mu, \nu_\tau$ with $\Delta m^2_{SUN} \simeq 7.6 \times 10^{-5} \, \text{eV}^2$ (solar ν, KamLAND)

$\nu_\mu \to \nu_\tau$ with $\Delta m^2_{ATM} \simeq 2.5 \times 10^{-3} \, \text{eV}^2$ (atm. ν, K2K, MINOS)

Bilarge 3ν-Mixing with $|U_{e3}|^2 \ll 1$ (CHOOZ)

β Decay, Cosmology, $\beta\beta_{0\nu}$ Decay $\Longrightarrow m_\nu \lesssim 1 \, \text{eV}$

FUTURE

Theory: Why lepton mixing $\neq$ quark mixing?
Why only $|U_{e3}|^2 \ll 1$?
Improve calculation of $\mathcal{M}_{0\nu}$!
LSND and MiniBooNE Low-Energy Anomaly?

Exp.: Measure $|U_{e3}| > 0 \Rightarrow$ CP violation, matter eff., mass hierarchy
Check $\beta\beta_{0\nu}$ signal at Quasi-Degenerate mass scale
Improve β Decay, Cosmology, $\beta\beta_{0\nu}$ Decay measurements
LSND and MiniBooNE Low-Energy Anomaly?