Neutrino Physics: Status and Perspectives

Carlo Giunti

INFN, Sezione di Torino, and
Dipartimento di Fisica Teorica, Università di Torino
mailto://giunti@to.infn.it

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

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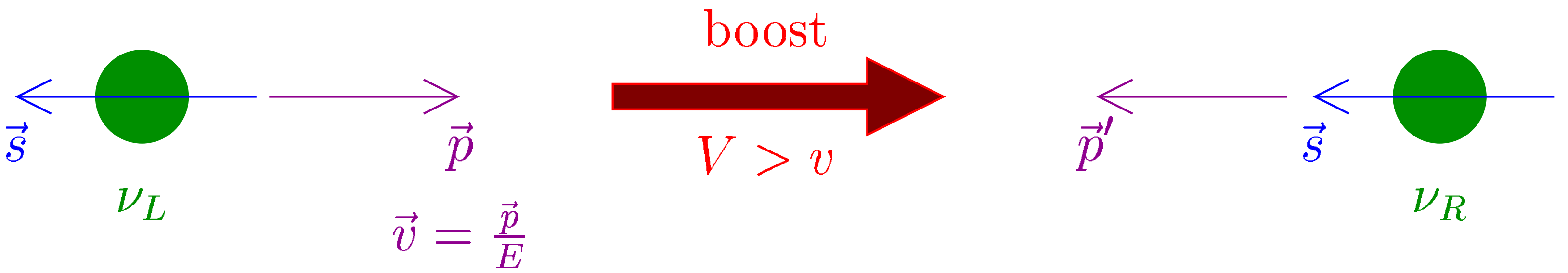
Introduction to Neutrino Masses, Mixing and Oscillations

Solar $\nu_e \to \nu_\mu, \nu_\tau$ + Atmospheric $\nu_\mu \to \nu_\tau \Longrightarrow$ 3-ν Mixing

Absolute Scale of Neutrino Masses

Neutrino Mass



Standard Model: $\nu_L, \nu_R^c \Longrightarrow$ no Dirac mass term $\mathcal{L}^{\rm D} \sim m^{\rm D} \left(\overline{\nu_L} \nu_R + \overline{\nu_R} \nu_L \right)$

(no ν_R, ν_L^c)

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

$$\nu_R^c \equiv \nu_R \Longrightarrow \text{Majorana mass term } \mathcal{L}^{\rm M} \sim m^{\rm M} \left(\overline{\nu_L} \nu_R^c + \overline{\nu_R^c} \nu_L \right)$$

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

(no Higgs triplet)

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 mass term $\mathcal{L}^{\mathrm{D}} \sim m^{\mathrm{D}} \left(\overline{\nu_L} \nu_R + \overline{\nu_R} \nu_L \right) \Rightarrow m^{\mathrm{D}} \lesssim 100\,\mathrm{GeV}$

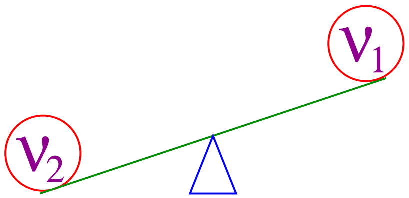
surprise: Majorana mass for ν_R is allowed! $\quad \mathcal{L}^{\mathrm{M}}_R \sim m^{\mathrm{M}}_R \left(\overline{\nu^c_L} \nu_R + \overline{\nu_R} \nu^c_L \right)$

total neutrino mass term $\quad \mathcal{L}^{\mathrm{D+M}} \sim \begin{pmatrix} \overline{\nu_L} & \overline{\nu^c_L} \end{pmatrix} \begin{pmatrix} 0 & m^{\mathrm{D}} \\ m^{\mathrm{D}} & m^{\mathrm{M}}_R \end{pmatrix} \begin{pmatrix} \nu^c_R \\ \nu_R \end{pmatrix}$

m^{M}_R can be arbitrarily large (not protected by SM symmetries)

$m^{\mathrm{M}}_R \sim$ scale of new physics beyond Standard Model $\Rightarrow m^{\mathrm{M}}_R \gg m^{\mathrm{D}}$

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



see-saw mechanism

natural explanation of
smallness of neutrino masses

massive neutrinos are Majorana!

[Minkowski, PLB 67 (1977) 42; Yanagida (1979); Gell-Mann, Ramond, Slansky (1979); Mohapatra, Senjanovic, PRL 44 (1980) 912]

Standard Model: Lepton numbers are conserved

	L_e	L_μ	L_τ
$(\nu_e\,,\,e^-)$	$+1$	0	0
$(\nu_\mu\,,\,\mu^-)$	0	$+1$	0
$(\nu_\tau\,,\,\tau^-)$	0	0	$+1$

	L_e	L_μ	L_τ
$(\nu_e^c\,,\,e^+)$	-1	0	0
$(\nu_\mu^c\,,\,\mu^+)$	0	-1	0
$(\nu_\tau^c\,,\,\tau^+)$	0	0	-1

$$\boxed{L = L_e + L_\mu + L_\tau}$$

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

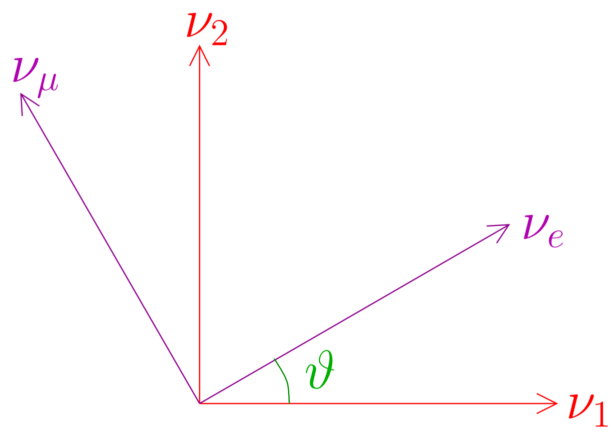
L_e, L_μ, L_τ are not conserved, but L is conserved $L(\nu_{\alpha R}) = L(\nu_{\beta L}) \Rightarrow |\Delta L| = 0$

Majorana mass term $m^{\rm M}\overline{\nu_L}\nu_R^c \Rightarrow \begin{pmatrix}\overline{\nu_{eL}} & \overline{\nu_{\mu L}} & \overline{\nu_{\tau L}}\end{pmatrix}\begin{pmatrix} m^{\rm M}_{ee} & m^{\rm M}_{e\mu} & m^{\rm M}_{e\tau} \\ m^{\rm M}_{\mu e} & m^{\rm M}_{\mu\mu} & m^{\rm M}_{\mu\tau} \\ m^{\rm M}_{\tau e} & m^{\rm M}_{\tau\mu} & m^{\rm M}_{\tau\tau}\end{pmatrix}\begin{pmatrix}\nu^c_{eR} \\ \nu^c_{\mu R} \\ \nu^c_{\tau R}\end{pmatrix}$

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

Two-Neutrino Mixing and Oscillations

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



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

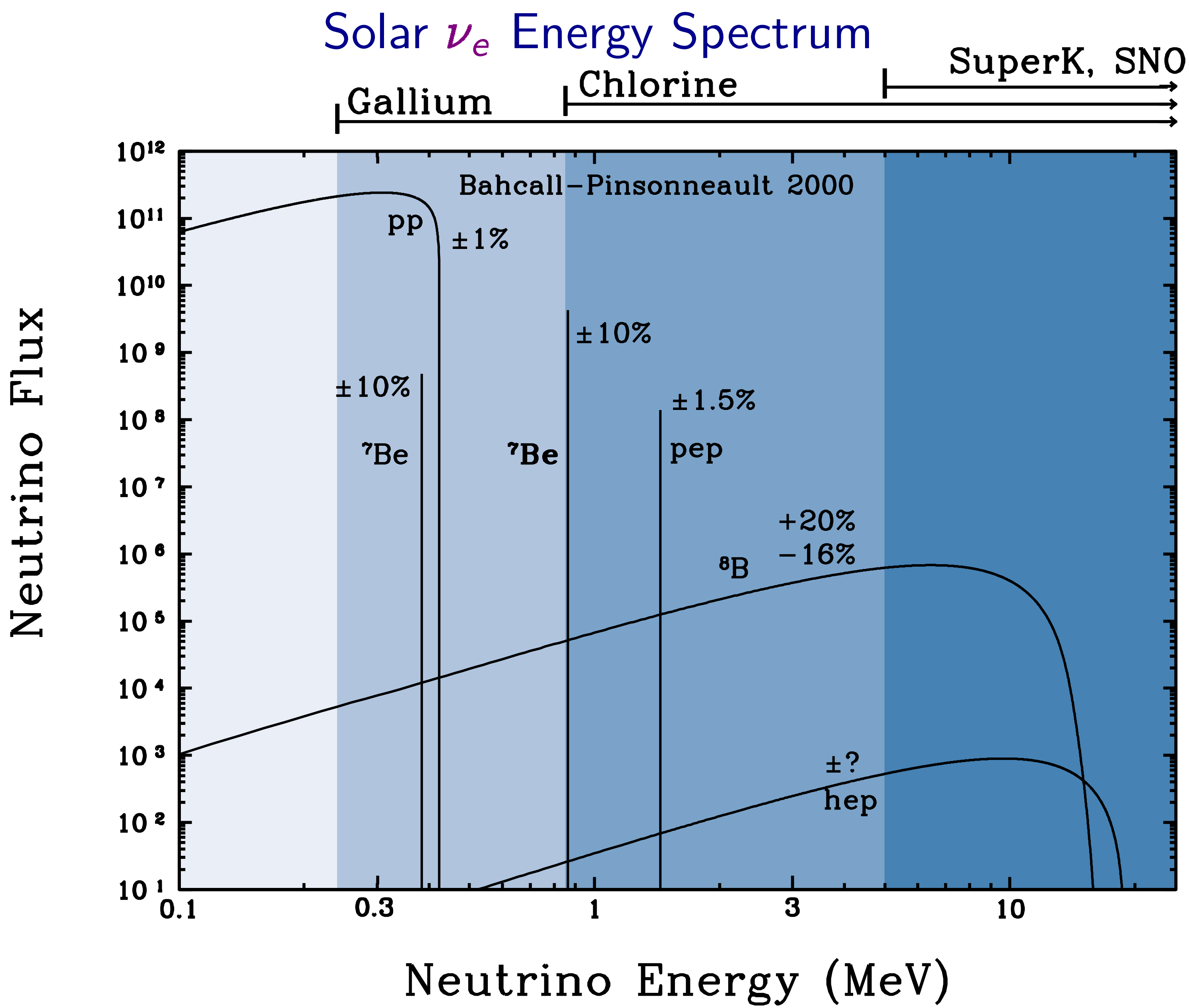
$$\boxed{\begin{array}{l} |\nu_e\rangle = \cos\vartheta\,|\nu_1\rangle + \sin\vartheta\,|\nu_2\rangle \\ |\nu_\mu\rangle = -\sin\vartheta\,|\nu_1\rangle + \cos\vartheta\,|\nu_2\rangle \end{array}}$$

$$\Delta m^2 \equiv \Delta m^2_{21} \equiv m^2_2 - m^2_1$$

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

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

Solar Neutrinos



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

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

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

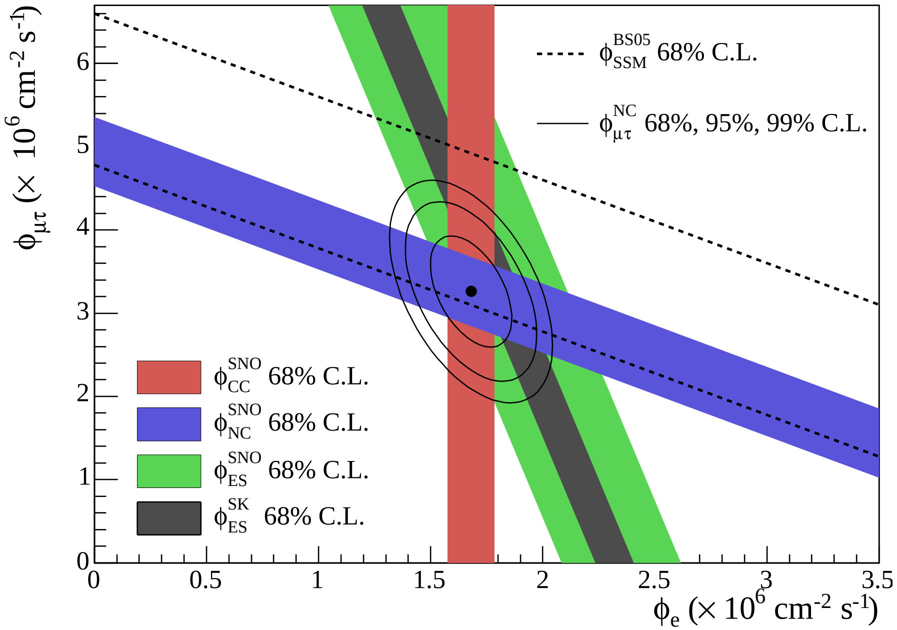
$$\Phi^{\text{SNO}}_{\nu_e,\nu_\mu,\nu_\tau} = 5.09 \pm 0.66 \times 10^6 \, \text{cm}^{-2} \, \text{s}^{-1}$$

SNO solved
solar neutrino problem

$\Downarrow$

Neutrino Physics
(April 2002)

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



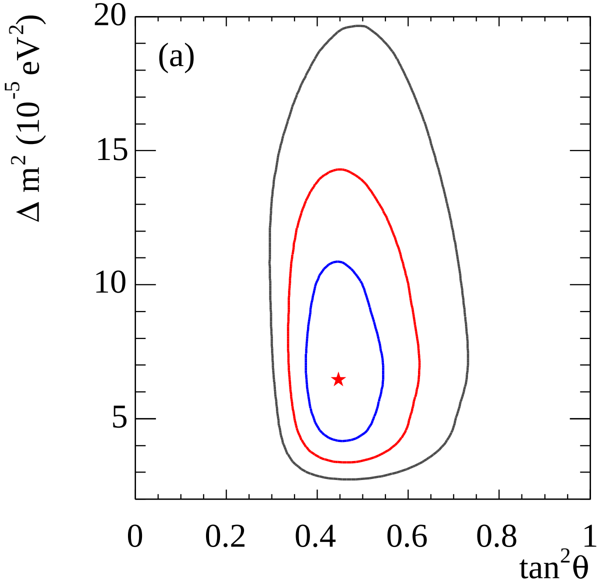
$\nu_e \to \nu_\mu, \nu_\tau$ oscillations

$\Downarrow$

LMA: Large Mixing Angle solution

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

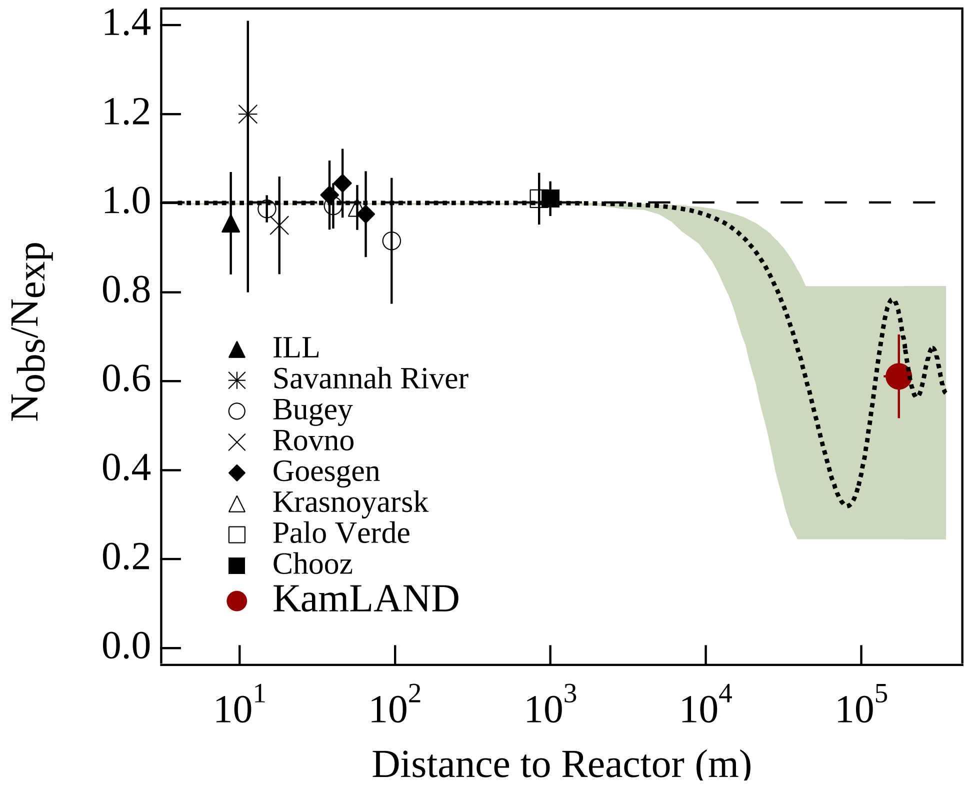
$$\tan^2 \vartheta \simeq 0.45^{+0.09}_{-0.08}$$

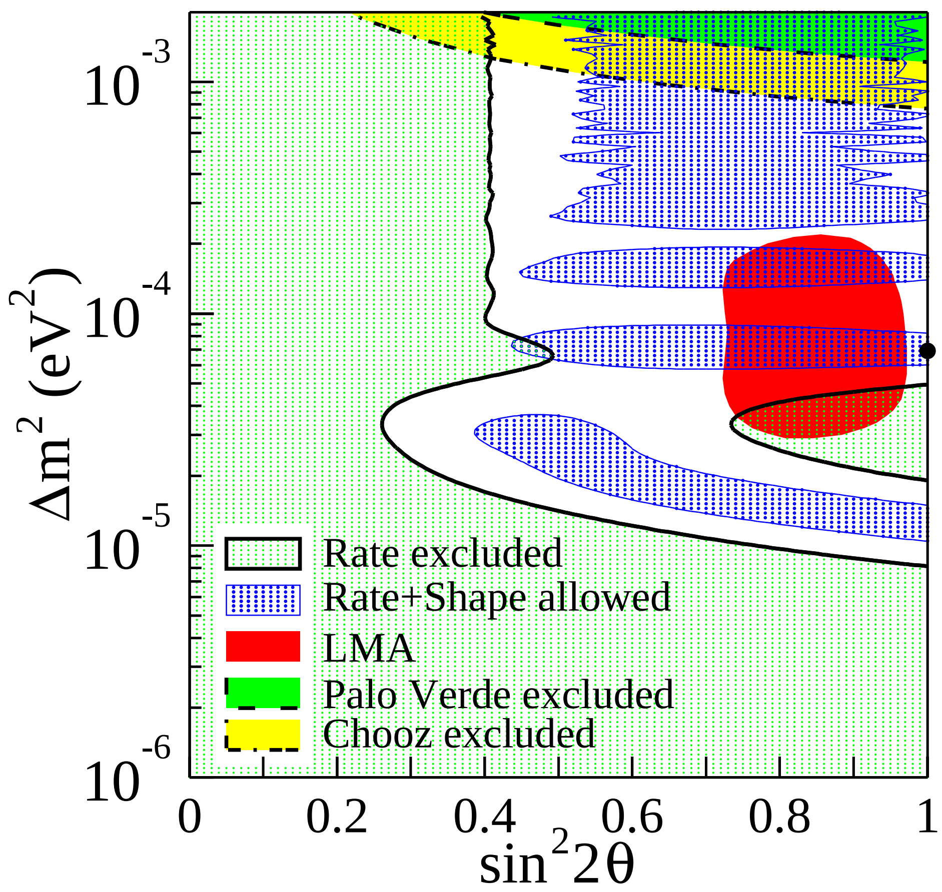


[SNO, PRC 72 (2005) 055502, nucl-ex/0502021]

KamLAND

Reactor $\bar{\nu}_e \to \bar{\nu}_e$: confirmation of LMA (December 2002)





Shade: 95% C.L. LMA

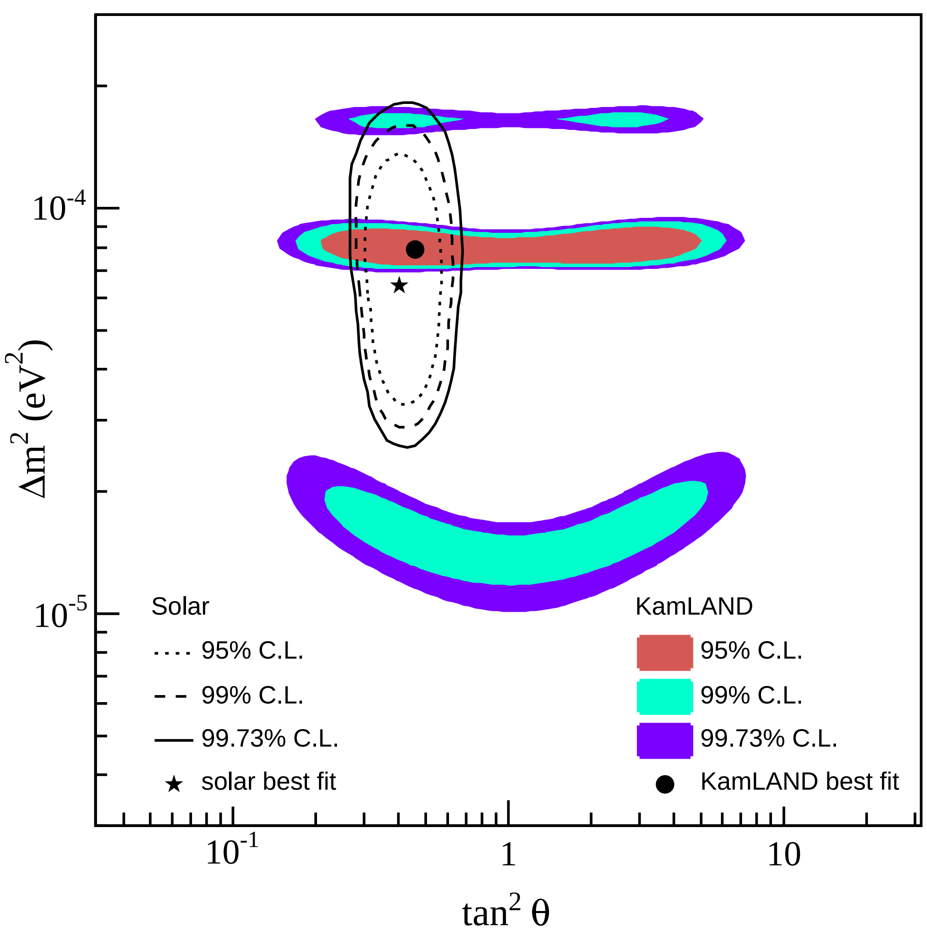
95% C.L.

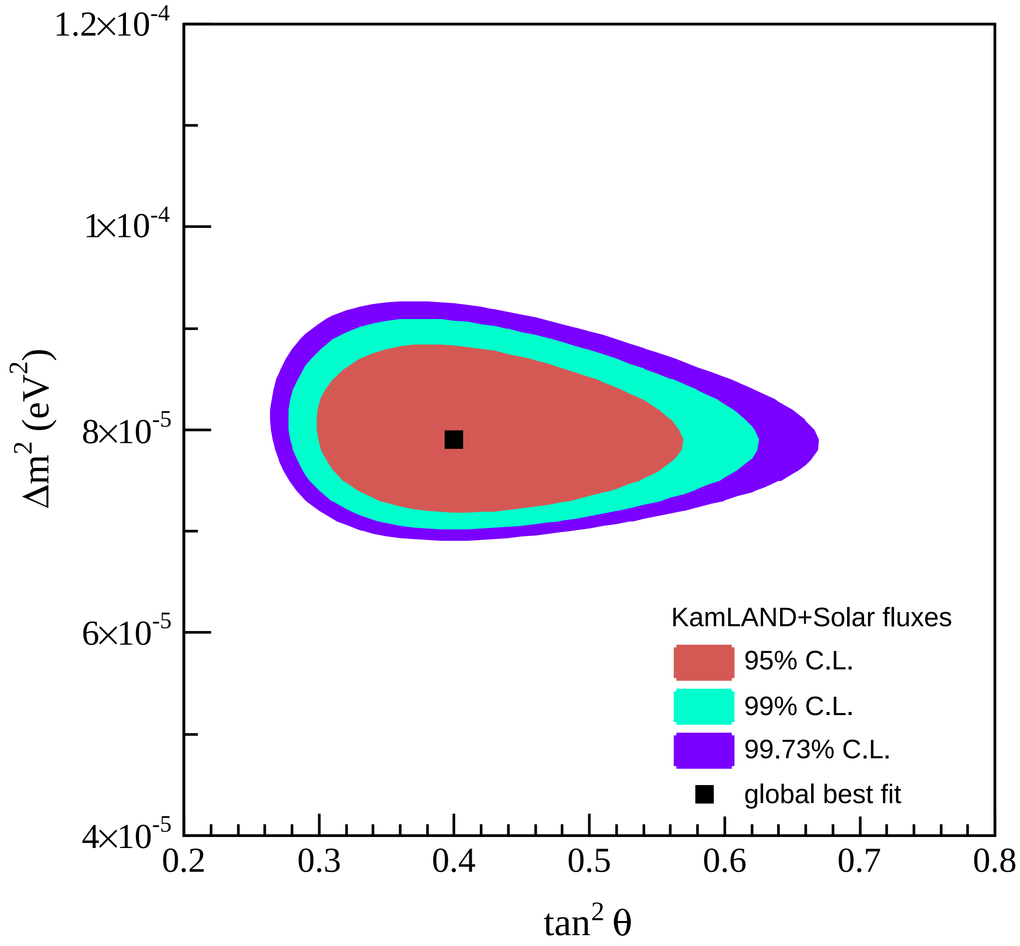
Curve: $\begin{cases} \Delta m^2 = 5.5 \times 10^{-5}\,\text{eV}^2 \\ \sin^2 2\vartheta = 0.83 \end{cases}$

[KamLAND, PRL 90 (2003) 021802, hep-ex/0212021]

Combined Fit of Solar and Reactor Neutrino Data

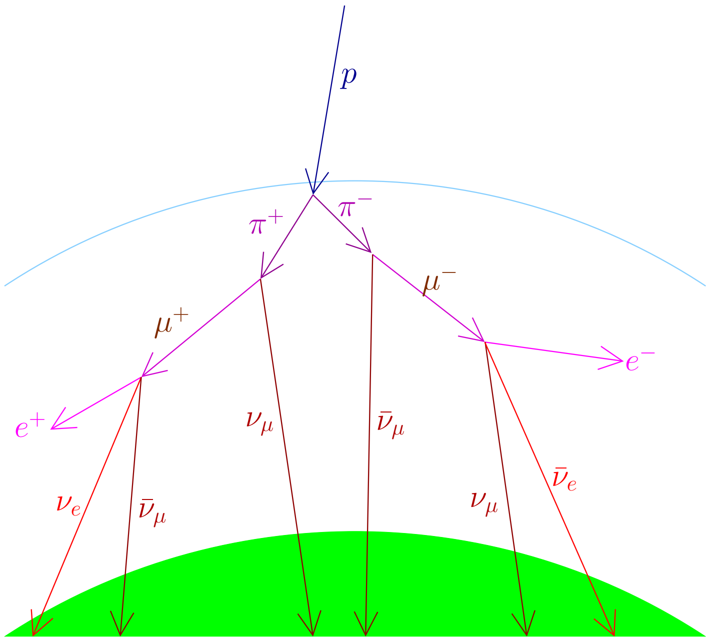
[KamLAND, hep-ex/0406035]

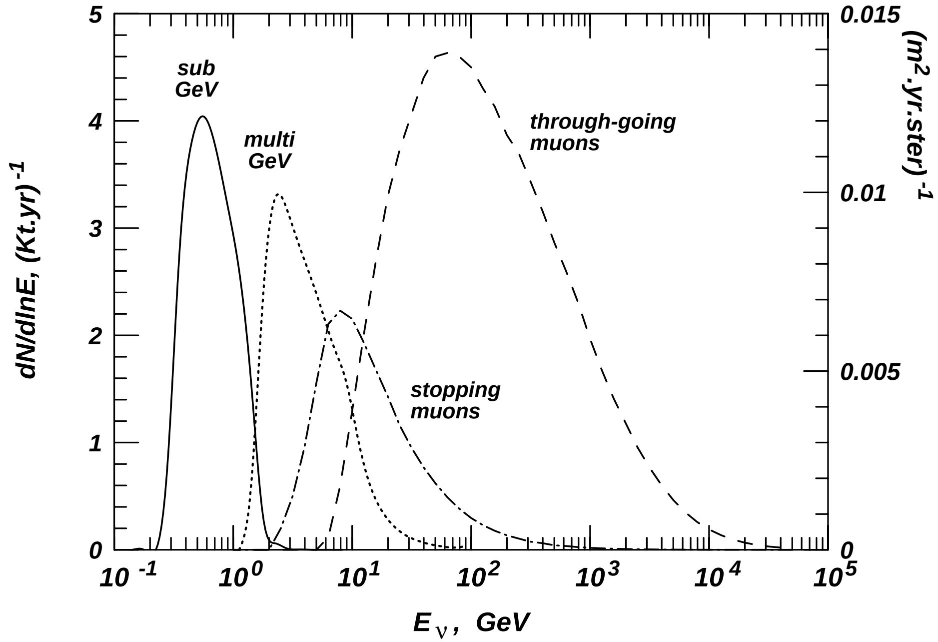




Best Fit: $\Delta m^2 = 0.82^{+0.6}_{-0.5} \times 10^{-5}\,\text{eV}^2$ $\tan^2\vartheta = 0.40^{+0.09}_{-0.07}$

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

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

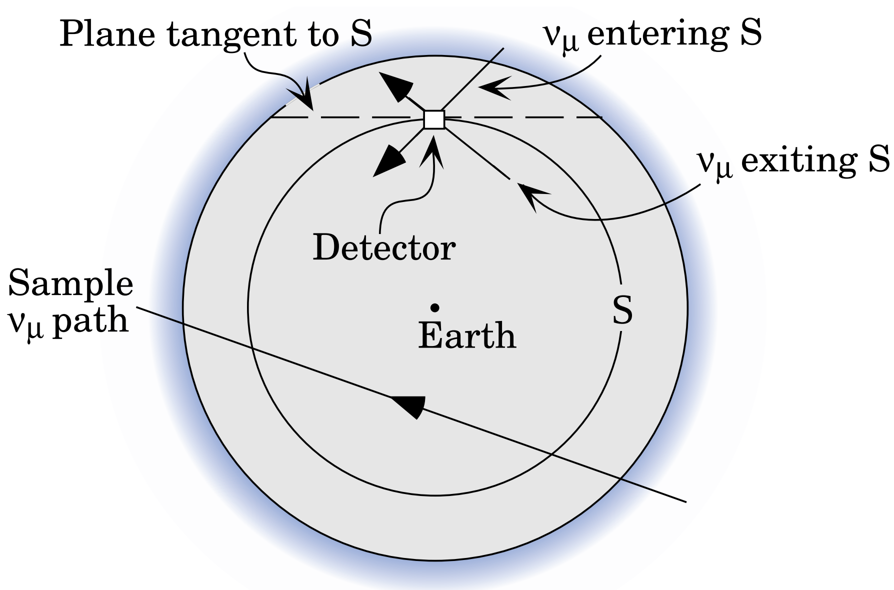
$$R^{\text{K}}_{\text{sub-GeV}} = 0.60 \pm 0.07 \pm 0.05$$

[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



- any path entering the sphere S later exits
- steady state $\Rightarrow$ $\Phi^{\text{in}}(S) = \Phi^{\text{out}}(S)$
- $E_\nu \gtrsim 1\,\text{GeV}$ $\Rightarrow$ isotropic flux of cosmic rays
- homogeneity $\Rightarrow$ $\Phi^{\text{in}}(s) = \Phi^{\text{out}}(s)$, $\forall s \in S$
- $\text{D} \in S$ $\Rightarrow$ $\Phi^{\text{up}}(\text{D}) = \Phi^{\text{down}}(\text{D})$,

[B. Kayser, Rev. Part. Prop., PRD 66 (2002) 010001]

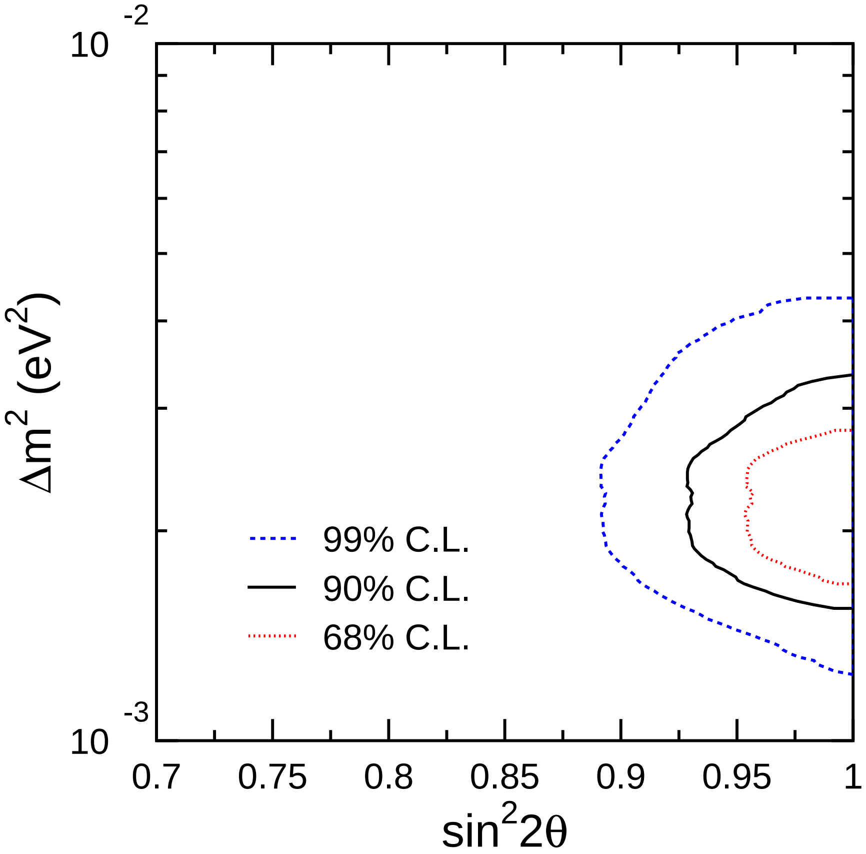
(December 1998)

$$\boxed{A_{\nu_\mu}^{\text{up-down}}(\text{SK}) = \left(\frac{N_{\nu_\mu}^{\text{up}} - N_{\nu_\mu}^{\text{down}}}{N_{\nu_\mu}^{\text{up}} + N_{\nu_\mu}^{\text{down}}} \right) = -0.296 \pm 0.048 \pm 0.01}$$

[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



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

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

1489.2 live-days (Apr 1996 – Jul 2001)

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

Measure of ν_τ CC Int. is Difficult:

- $E_{\text{th}} = 3.5\,\text{GeV} \Longrightarrow \sim 20$events/yr
- τ-Decay $\Longrightarrow$ Many Final States

ν_τ-Enriched Sample

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

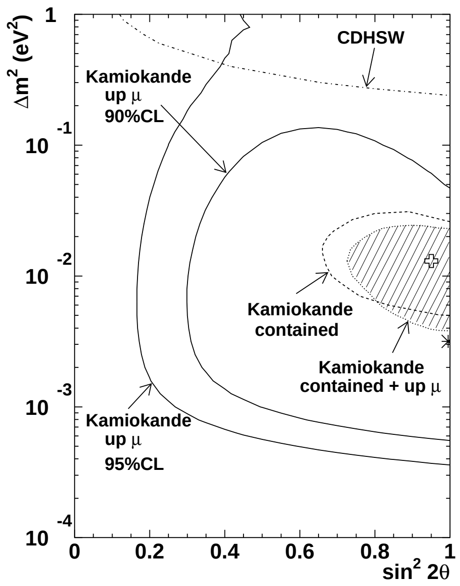
$$\boxed{N_{\nu_\tau}^{\text{exp}} = 138^{+50}_{-58}}$$

$N_{\nu_\tau} > 0$ @ 2.4σ

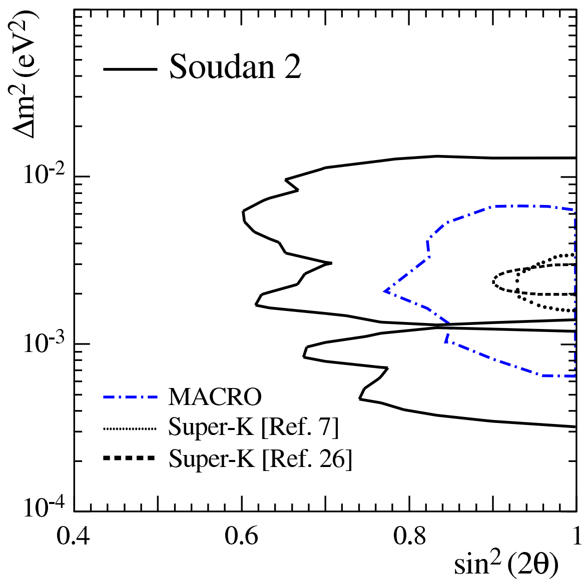
[Super-Kamiokande, hep-ex/0607059]

future: CNGS $\nu_\mu \to \nu_\tau$ (OPERA)

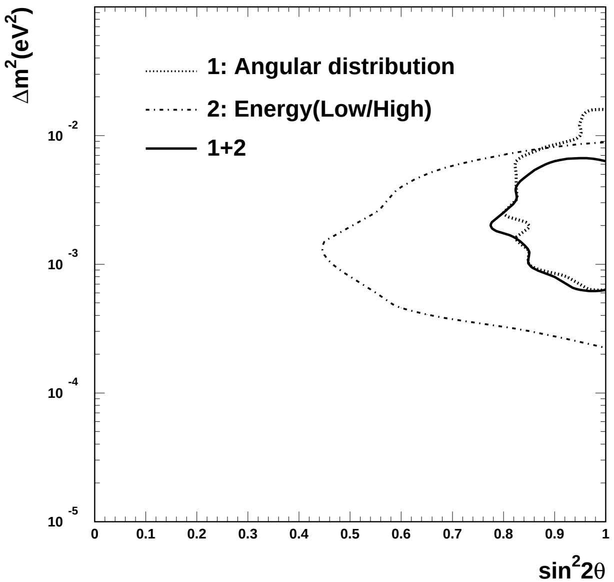
Kamiokande, Soudan-2, MACRO and MINOS



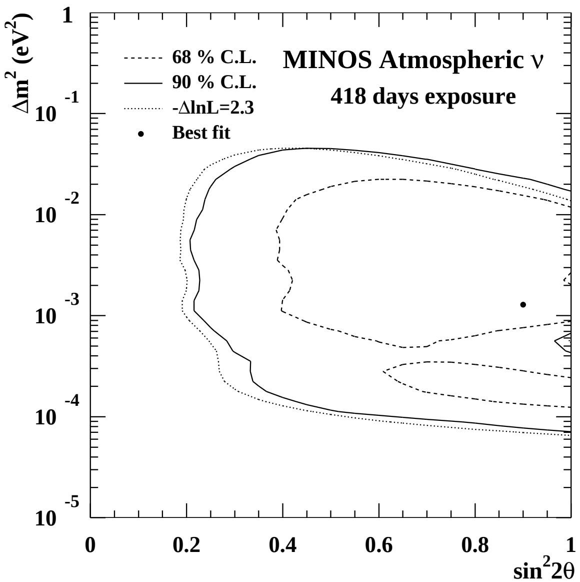
[Kamiokande, hep-ex/9806038]



[Soudan 2, hep-ex/0507068]



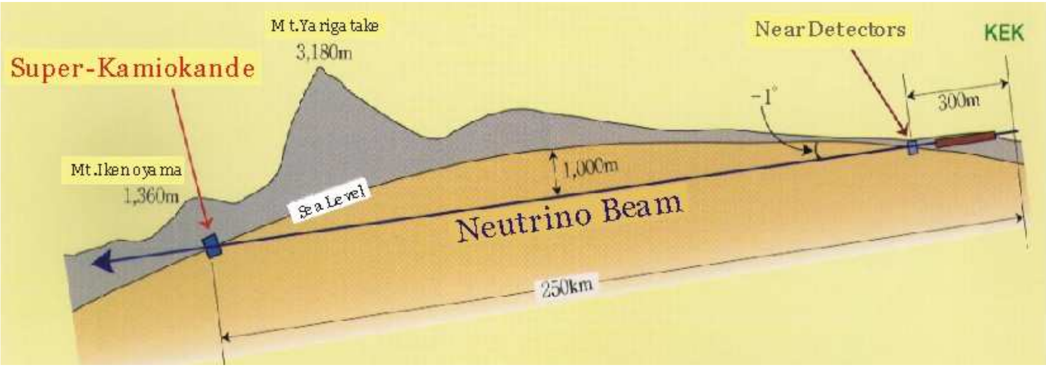
[MACRO, hep-ex/0304037]



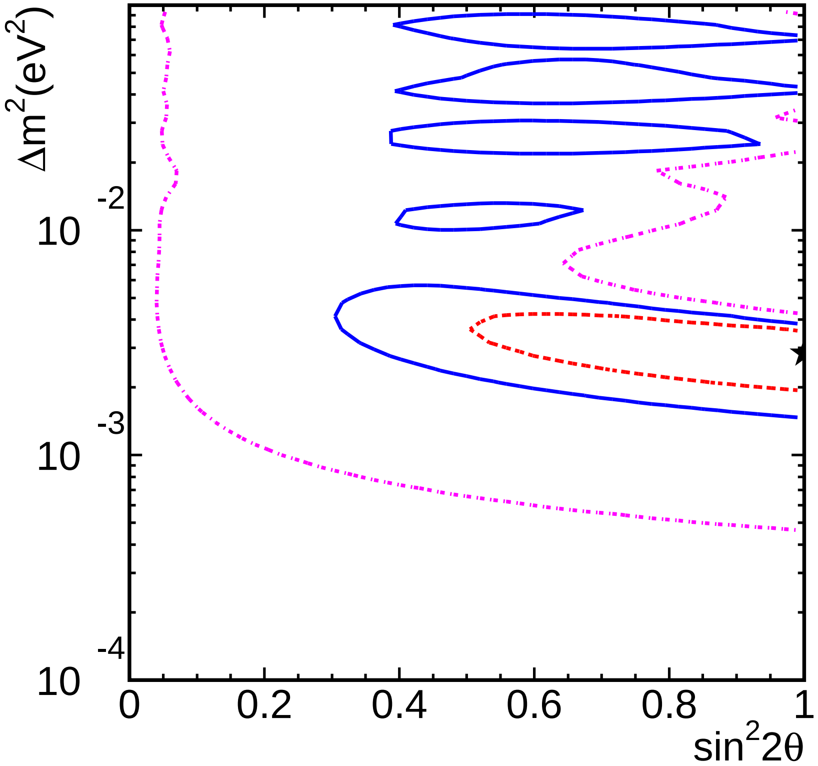
[MINOS, hep-ex/0512036]

K2K

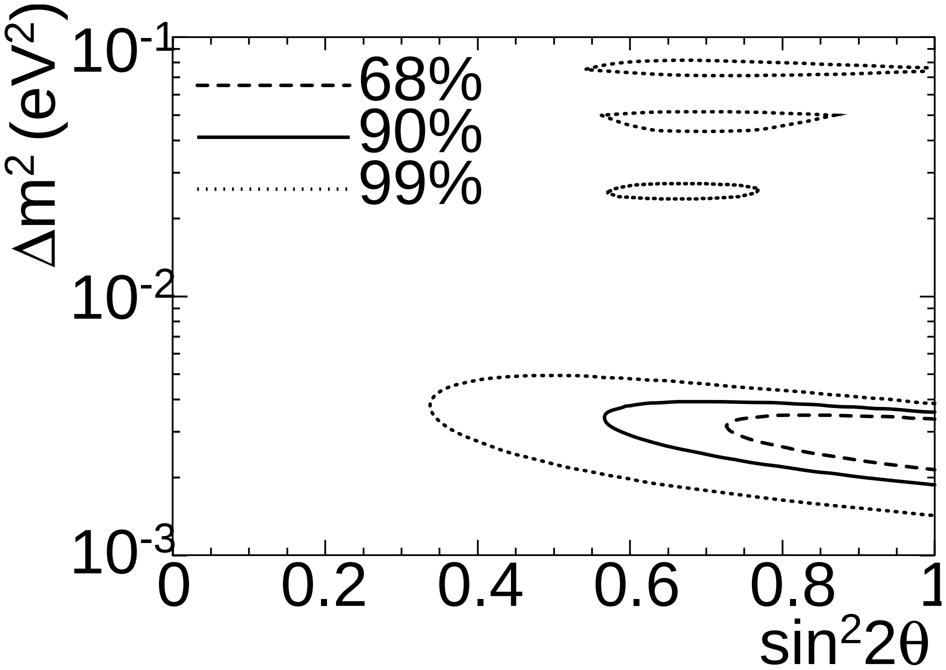
confirmation of atmospheric allowed region (June 2002)



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



[K2K, Phys. Rev. Lett. 90 (2003) 041801]

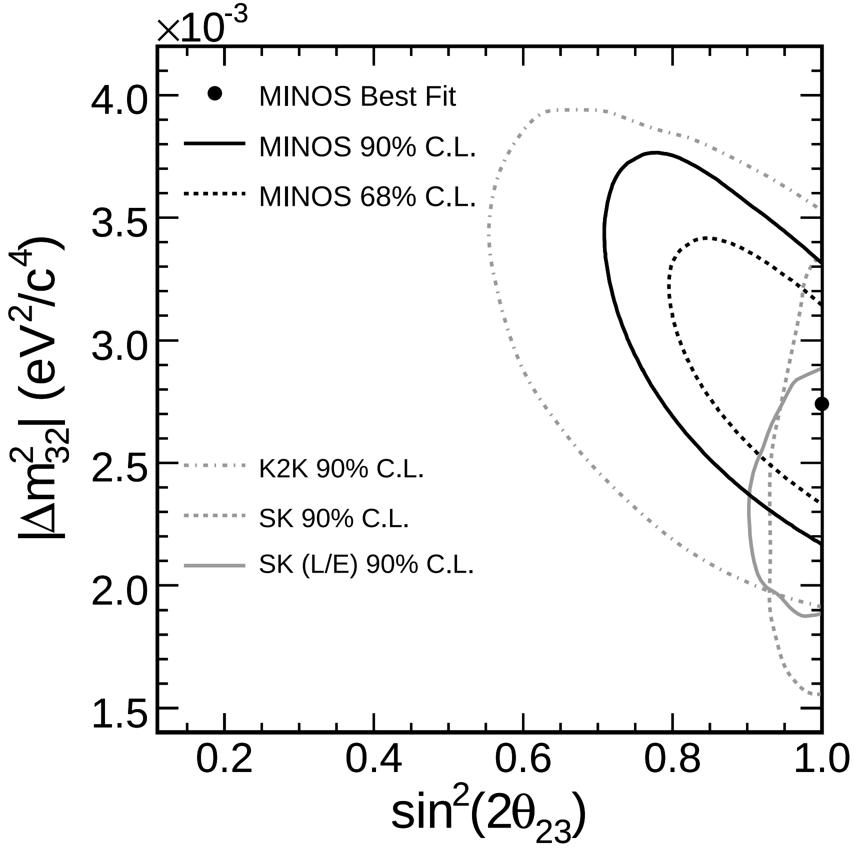


[K2K, hep-ex/0411038]

MINOS

May 2005 – Feb 2006

http://www-numi.fnal.gov/



Near Detector: 1 km

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

$$\Delta m^2 = 2.74^{+0.44}_{-0.26} \times 10^{-3}\,\text{eV}^2$$

$\sin^2 2\vartheta > 0.87$ @ $68\%\,CL$

[MINOS, hep-ex/0607088]

Experimental Evidences of Neutrino Oscillations

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

Reactor
$\bar{\nu}_e$ disappearance

Homestake
Kamiokande
GALLEX/GNO
SAGE
Super-Kamiokande

(KamLAND)

$\xrightarrow{2\sigma}$

$$\Delta m^2_{\text{SUN}} = 7.92\,(1 \pm 0.09) \times 10^{-5}\,\text{eV}^2$$

$$\sin^2\vartheta_{\text{SUN}} = 0.314\,\left(1^{+0.18}_{-0.15}\right)$$

[Fogli et al, PPNP 57 (2006) 742, hep-ph/0506083]

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

Accelerator
ν_μ disappearance

Kamiokande
IMB
Super-Kamiokande
MACRO
Soudan-2

(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, hep-ph/0608060]

Three-Neutrino Mixing

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

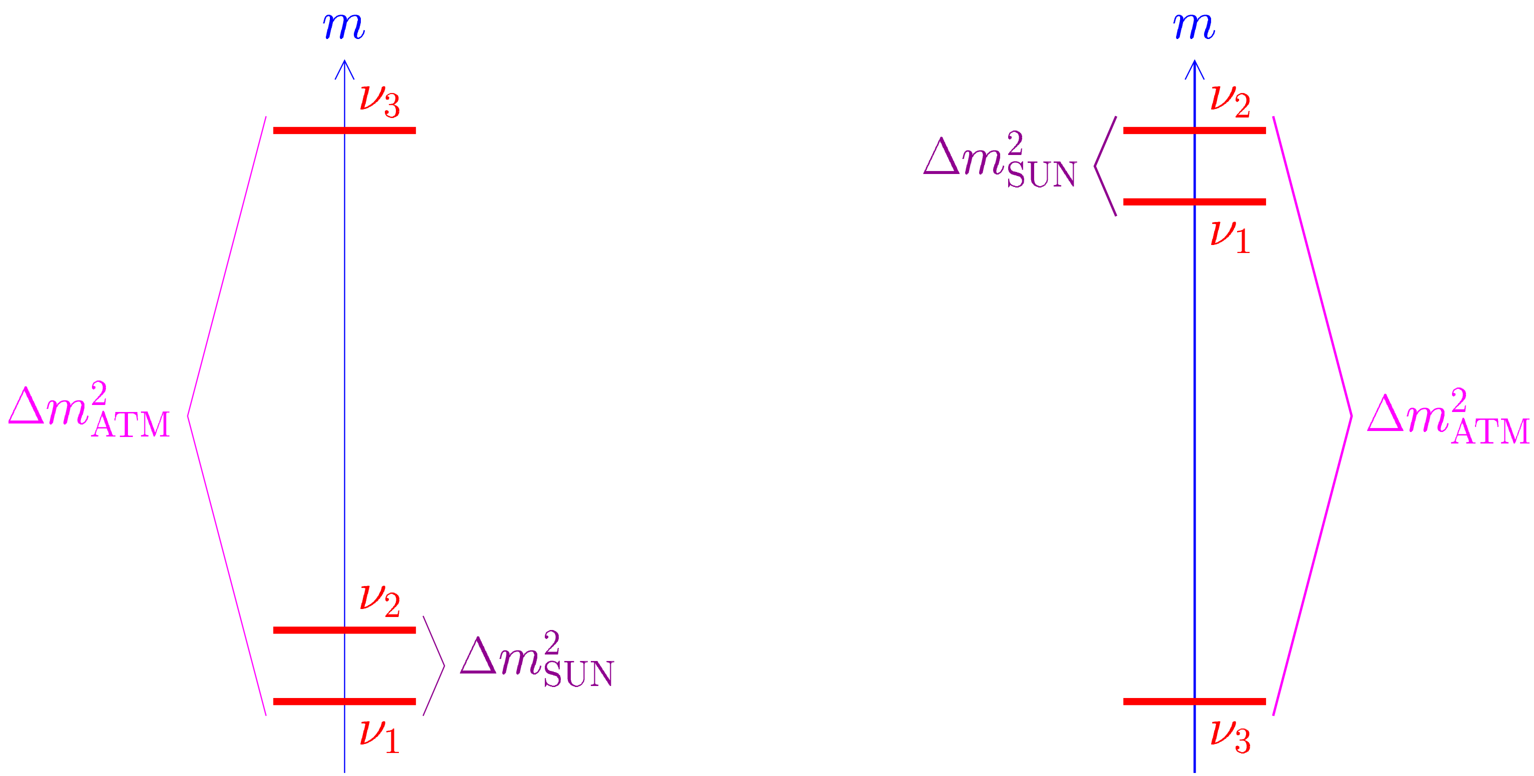
three flavor fields ν_e, ν_μ, ν_τ

three massive fields ν_1, ν_2, ν_3

$$\Delta m^2_{\mathrm{SUN}} = \Delta m^2_{21} \simeq 8.0 \times 10^{-5}\,\mathrm{eV}^2$$

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

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

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

$$U = \begin{array}{l} \text{SUN} \rightarrow \\ \\ \\ \end{array} \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

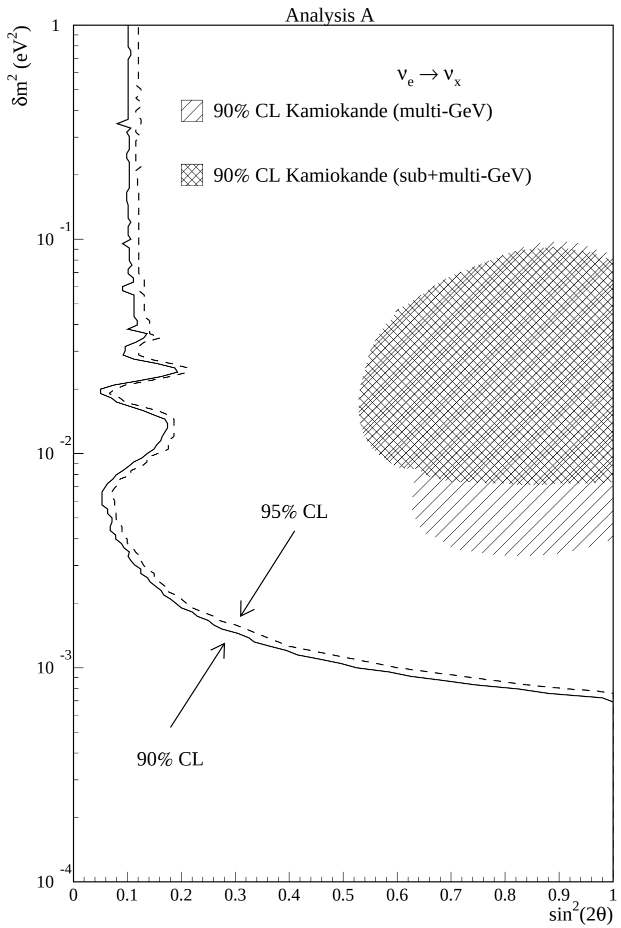
$\uparrow$ ATM

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

$$\Downarrow$$

$$\boxed{|U_{e3}|^2 < 5 \times 10^{-2} \quad (99.73\% \text{ C.L.})}$$

[Fogli et al., PRD 66 (2002) 093008]



[CHOOZ, PLB 466 (1999) 415]

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

SOLAR AND ATMOSPHERIC ν OSCILLATIONS
ARE PRACTICALLY DECOUPLED!

TWO-NEUTRINO SOLAR and ATMOSPHERIC ν OSCILLATIONS ARE OK!

$$\sin^2\vartheta_{\text{SUN}} = \frac{|U_{e2}|^2}{1 - |U_{e3}|^2} \simeq |U_{e2}|^2 \qquad \sin^2\vartheta_{\text{ATM}} = |U_{\mu 3}|^2$$

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

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

Standard Parameterization of Mixing Matrix

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\vartheta_{23} \simeq \vartheta_{\text{ATM}}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix}}_{\vartheta_{13} = \vartheta_{\text{CHOOZ}}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\vartheta_{12} = \vartheta_{\text{SUN}}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}}_{\beta\beta_{0\nu}}$$

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

$$\text{CHOOZ} + \text{SK} + \text{MINOS} \Longrightarrow \sin^2 \vartheta_{\text{CHOOZ}} = 0.008^{+0.023}_{-0.008} \ @ \ 2\sigma$$

[Fogli et al, hep-ph/0608060]

Global Fit of Oscillation Data: Bilarge Mixing

$$\Delta m^2_{21} = 7.92\,(1 \pm 0.09) \times 10^{-5}\,\mathrm{eV}^2 \qquad \sin^2\vartheta_{12} = 0.314\,(1^{+0.18}_{-0.15})$$

$$|\Delta m^2_{31}| = 2.6\,(1^{+0.14}_{-0.15}) \times 10^{-3}\,\mathrm{eV}^2 \qquad \sin^2\vartheta_{23} = 0.45\,(1^{+0.35}_{-0.20})$$

$$\sin^2\vartheta_{13} = 0.008^{+0.023}_{-0.008}$$

[Fogli et al, hep-ph/0608060]

$$|U|_{\mathrm{bf}} \simeq \begin{pmatrix} 0.82 & 0.56 & 0.09 \\ 0.37 - 0.47 & 0.58 - 0.65 & 0.67 \\ 0.32 - 0.43 & 0.52 - 0.59 & 0.74 \end{pmatrix}$$

$$|U|_{2\sigma} \simeq \begin{pmatrix} 0.78 - 0.86 & 0.51 - 0.61 & 0.00 - 0.18 \\ 0.21 - 0.57 & 0.41 - 0.74 & 0.59 - 0.78 \\ 0.19 - 0.56 & 0.39 - 0.72 & 0.62 - 0.80 \end{pmatrix}$$

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

Future Reactor Experiments

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \sin^2 2\vartheta_{13} \, \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \qquad \langle E \rangle \simeq 3.6\,\text{MeV}$$

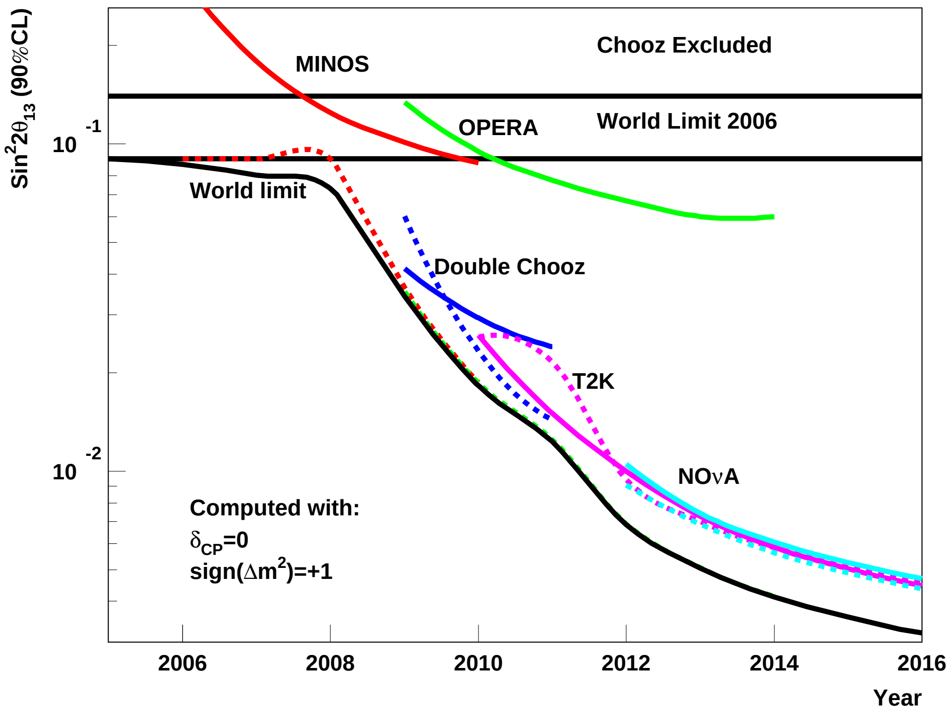
Exp.	Place	L (km)	Start (yr)	Duration (yr)	Sensitivity ($\sin^2 2\vartheta_{13}$)
Double-CHOOZ Far Detector	France	1.0	2008	1.5	0.06
Double-CHOOZ Near+Far	France	1.0	2010	3	0.03
KASKA	Japan		2010	3	0.02
RENO	Korea	1.5	2009	3	0.02
Daya Bay Near+Mid	China	1.0	2008	1	0.03
Daya Bay Near+Far	China	1.9	2010	3	0.01

Future Accelerator Experiments: Off-Axis

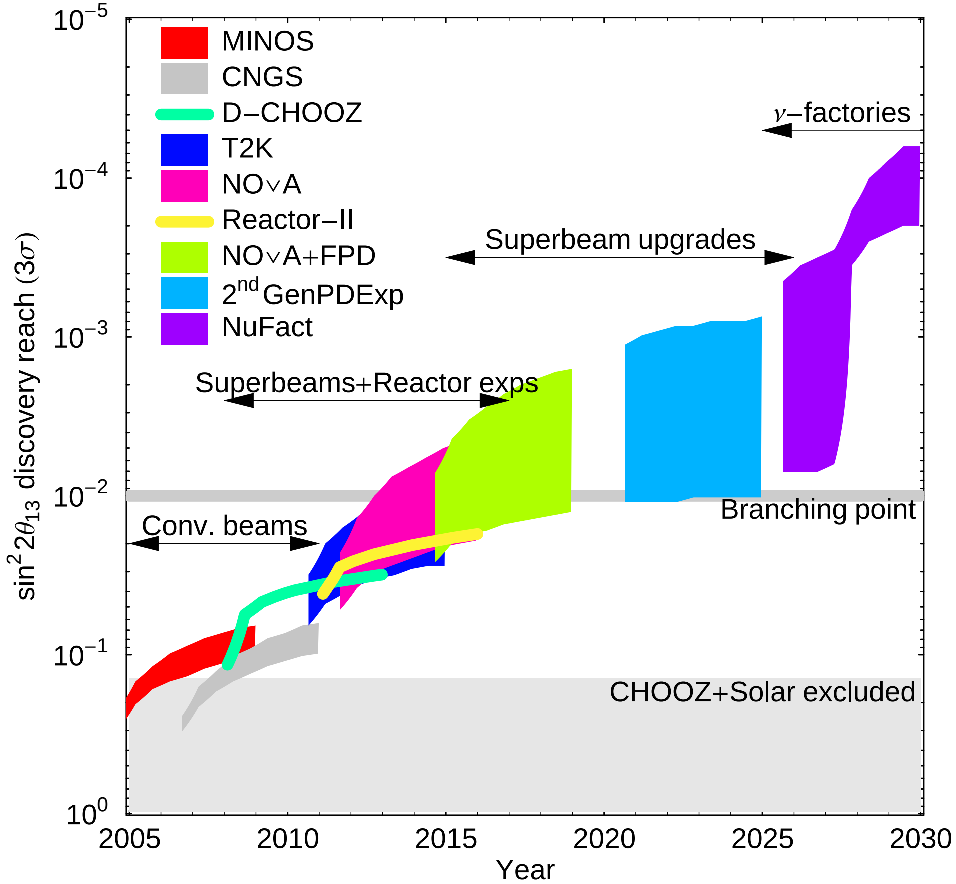
$$P_{\bar{\nu}_\mu \to \bar{\nu}_e} \simeq \sin^2 \vartheta_{23} \, \sin^2 2\vartheta_{13} \, \sin^2 \left(\frac{\Delta m^2_{31} L}{4E} \right)$$

Exp.	Place	$\langle E \rangle$ (GeV)	L (km)	Start (yr)	Duration (yr)	Sensitivity ($\sin^2 2\vartheta_{13}$)
T2K	Japan	0.7	295	2009	4	0.01
NOνA	USA	2	810	2011	4	0.01

The Hunt for ϑ_{13}



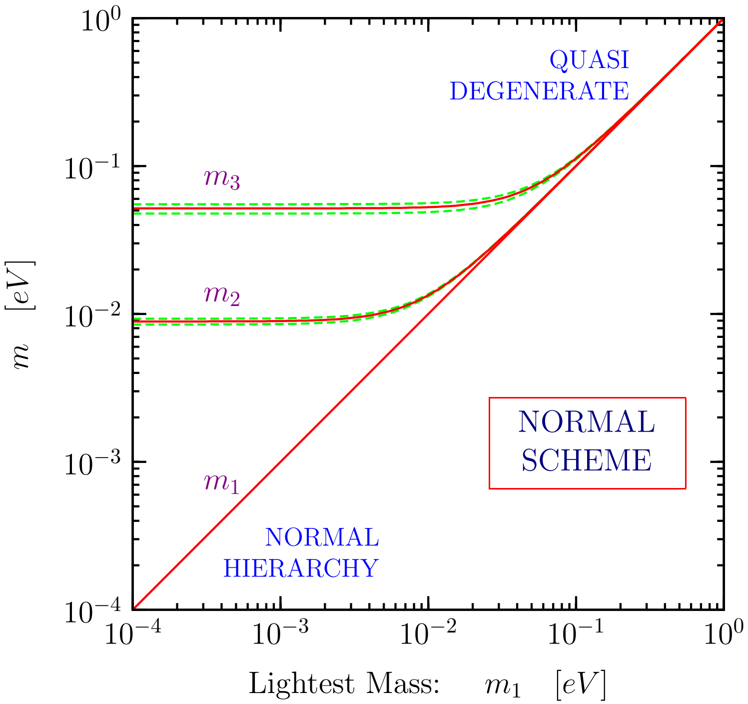
[Blondel et al, hep-ph/0606111]



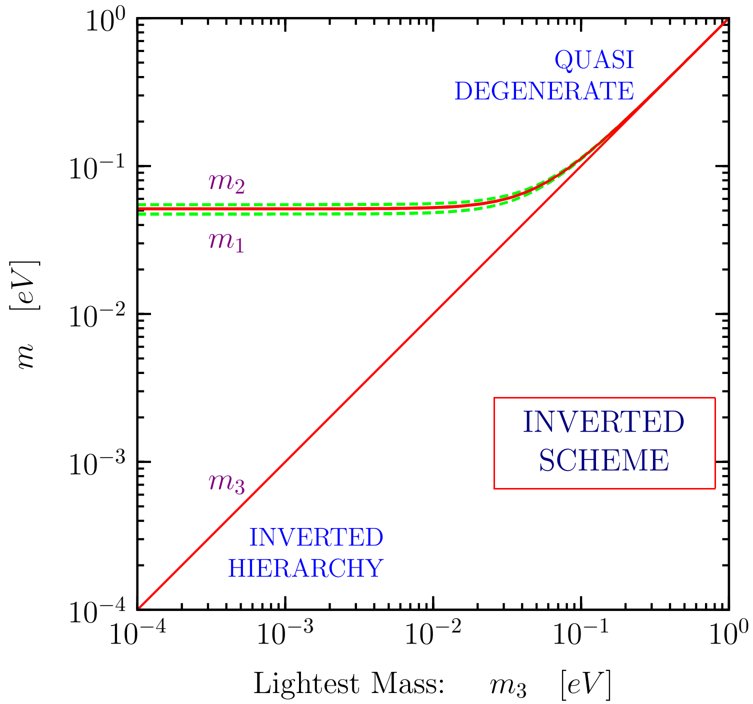
[Albrow et al, hep-ex/0509019]

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

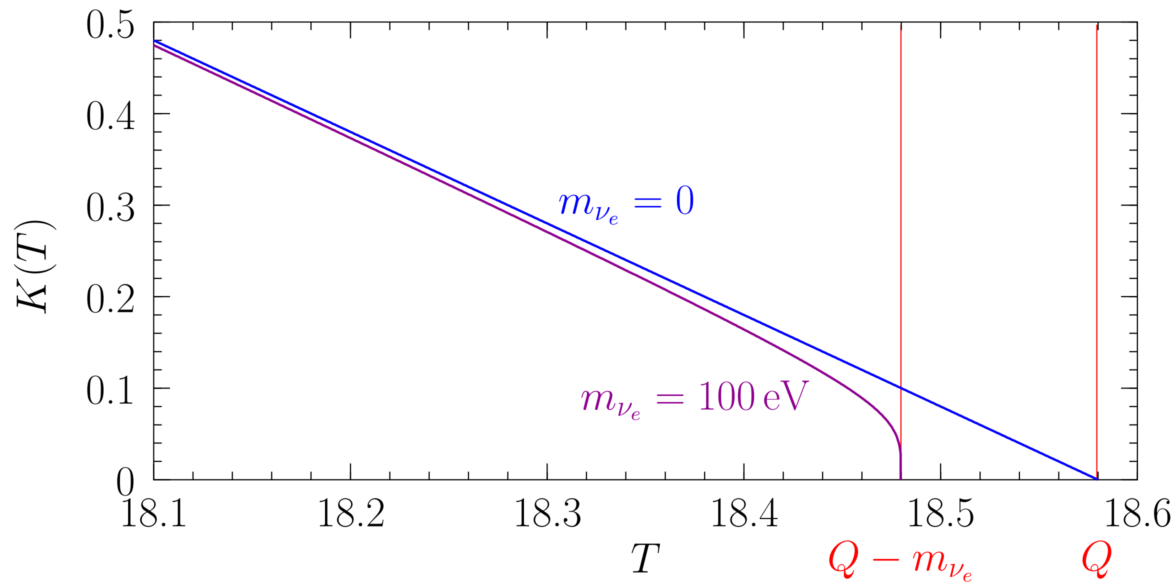
$^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$

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

$$Q = M_{^3\mathrm{H}} - M_{^3\mathrm{He}} - m_e = 18.58\,\mathrm{keV} \qquad m_{\nu_e}^2 = m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2$$

Kurie plot

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



$\boxed{m_{\nu_e} < 2.2\,\mathrm{eV} \quad (95\%\ \mathrm{C.L.})}$

Mainz & Troitsk

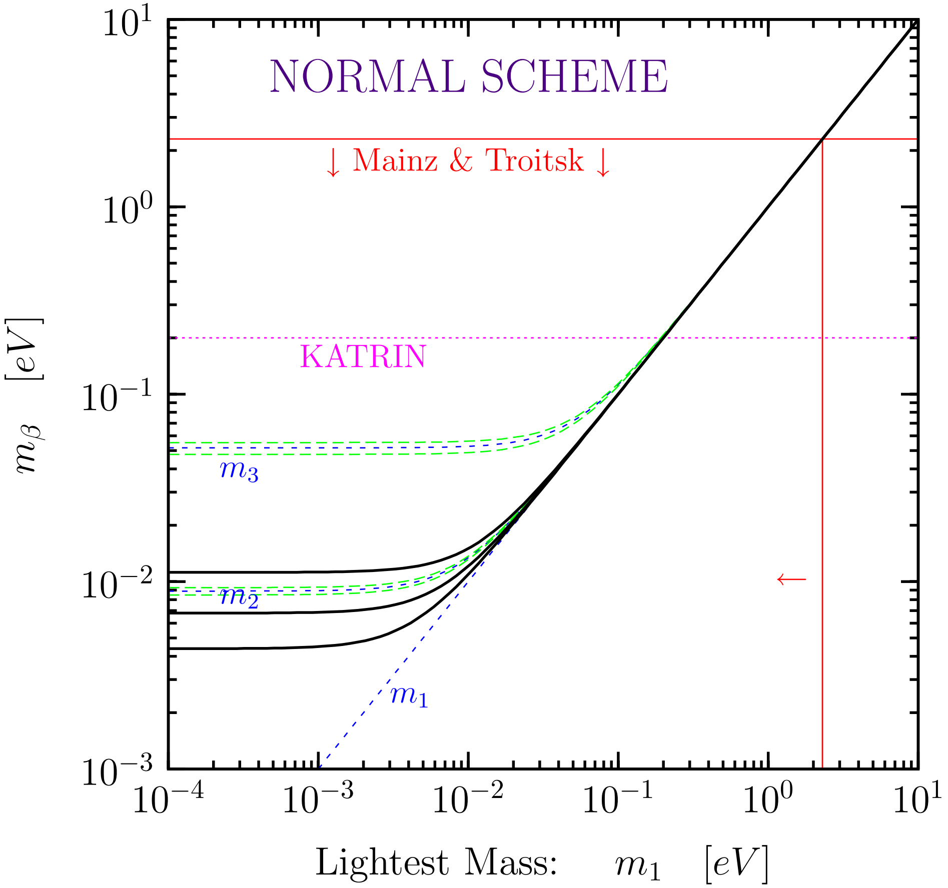
[Weinheimer, hep-ex/0210050]

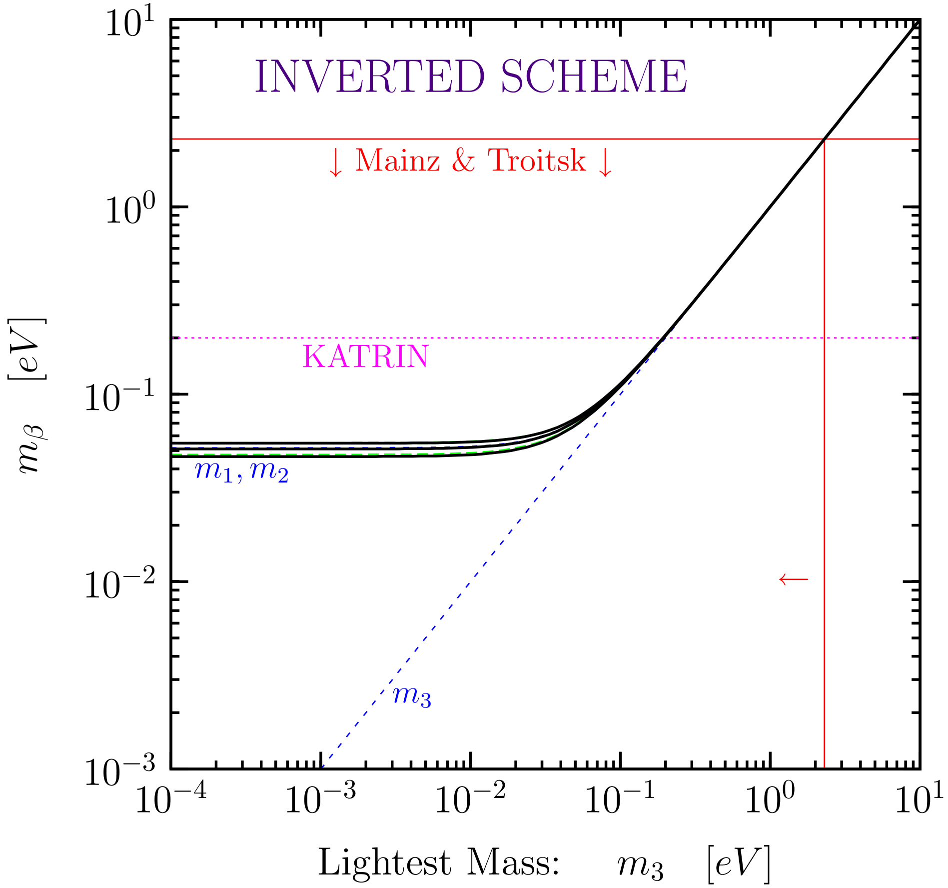
future: KATRIN (start 2010)

[hep-ex/0109033] [hep-ex/0309007]

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

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

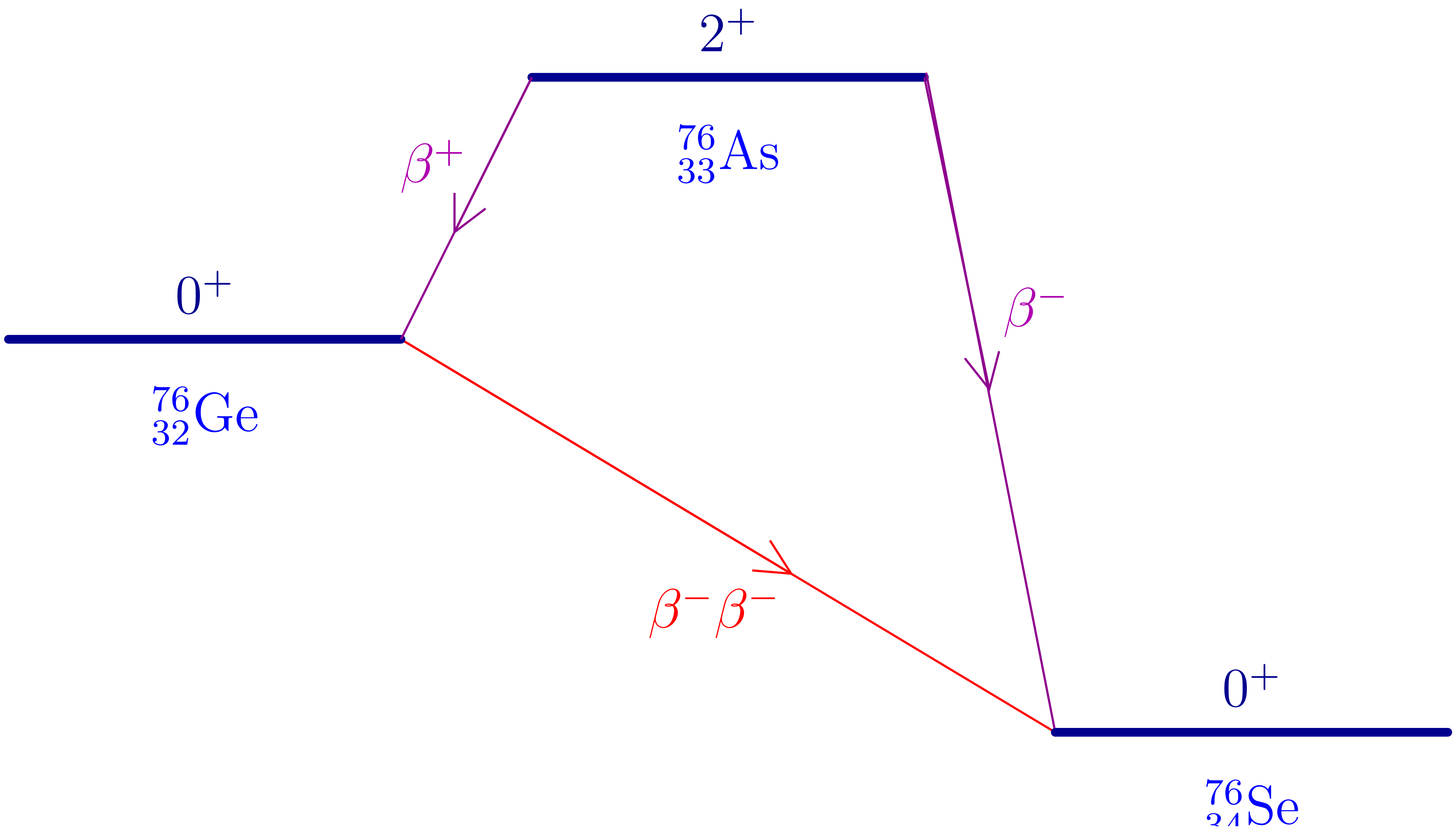




Quasi-Degenerate: $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \implies m_\beta^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2$

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

Neutrinoless Double-Beta Decay

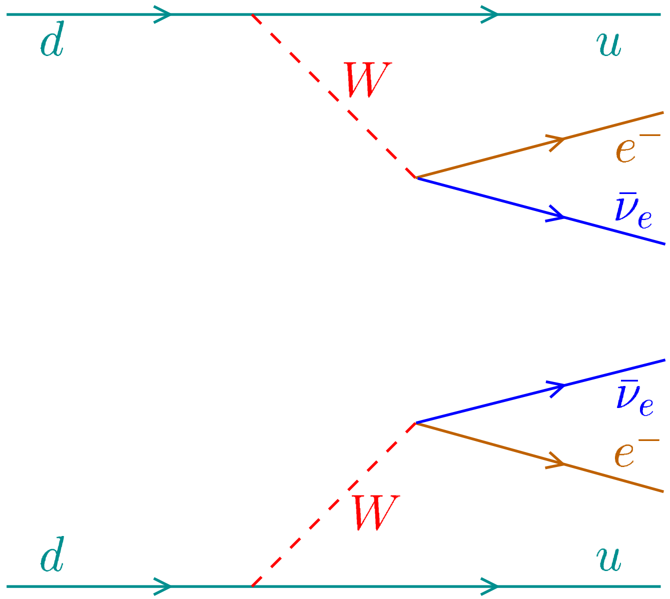


Two-Neutrino Double-β Decay: $\Delta L = 0$

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

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

second order weak interaction process in the Standard Model

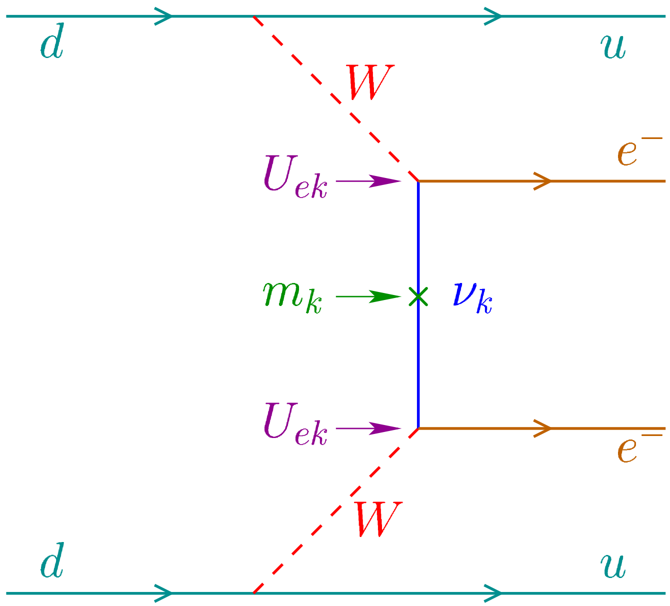


Neutrinoless Double-β Decay: $\Delta L = 2$

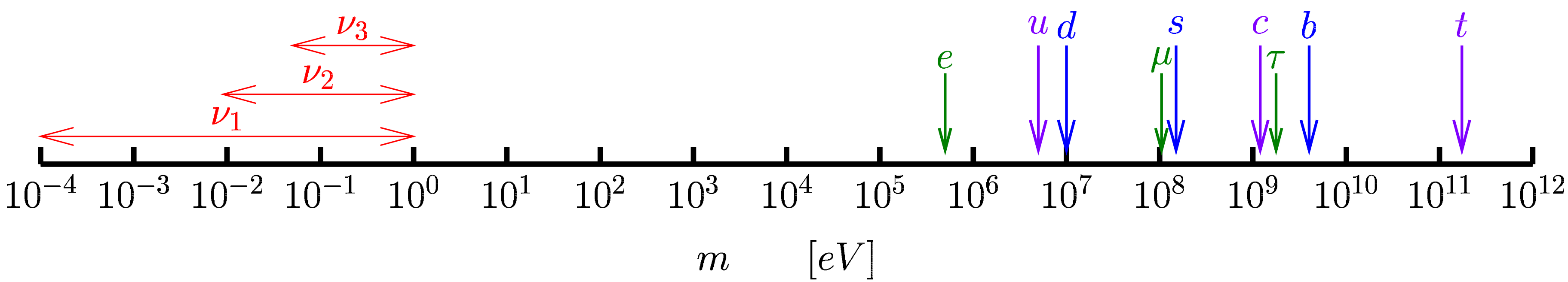
$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^-$$

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

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



Majorana Neutrino Mass?



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

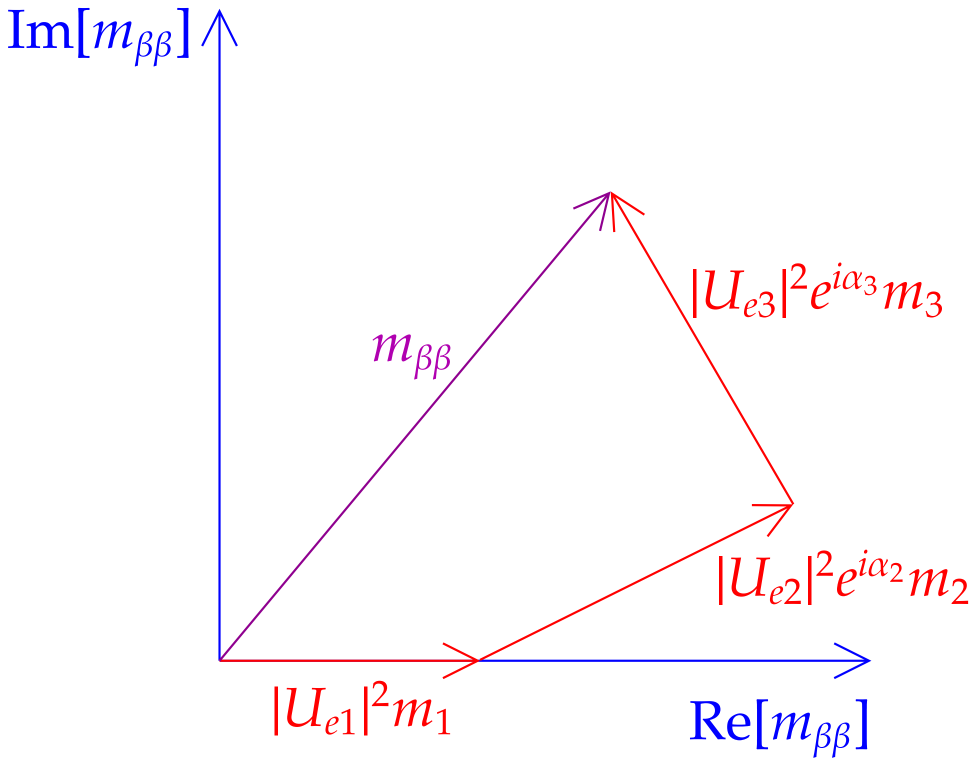
Majorana neutrino masses provide the most accessible window on New Physics Beyond the Standard Model

Effective Majorana Neutrino Mass

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

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

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



Experimental Bound

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

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

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

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

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

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

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

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

FUTURE EXPERIMENTS

NEMO 3, CUORICINO, COBRA, XMASS, CAMEO, CANDLES

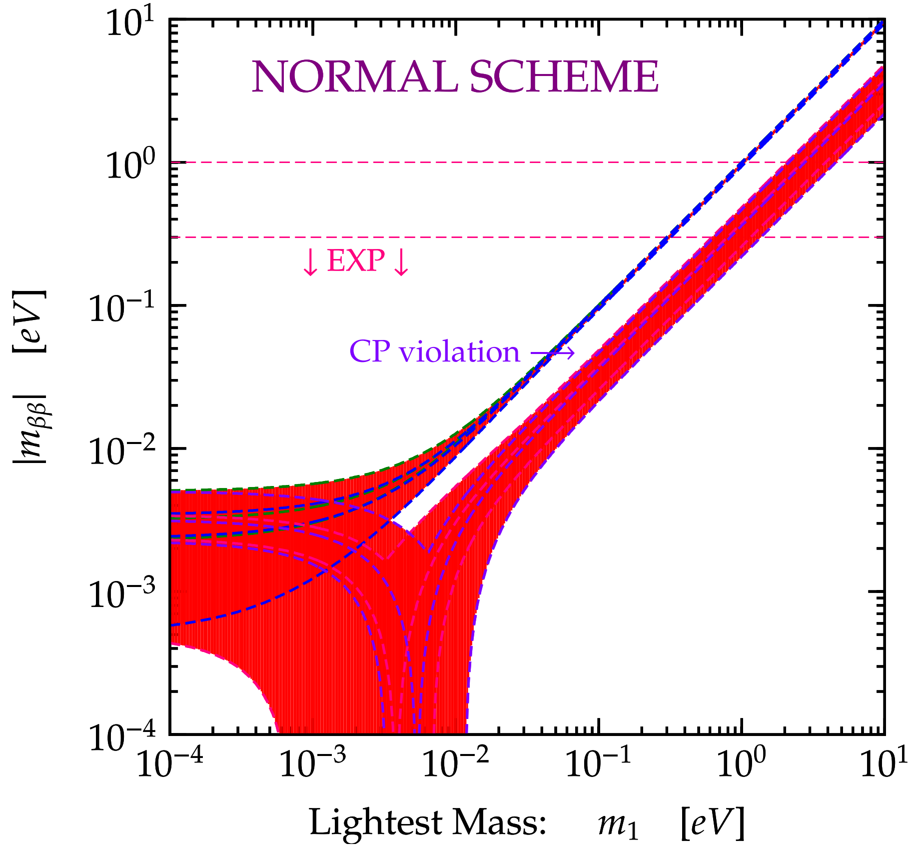
$$|m_{\beta\beta}| \sim \text{few}\ 10^{-1}\,\text{eV}$$

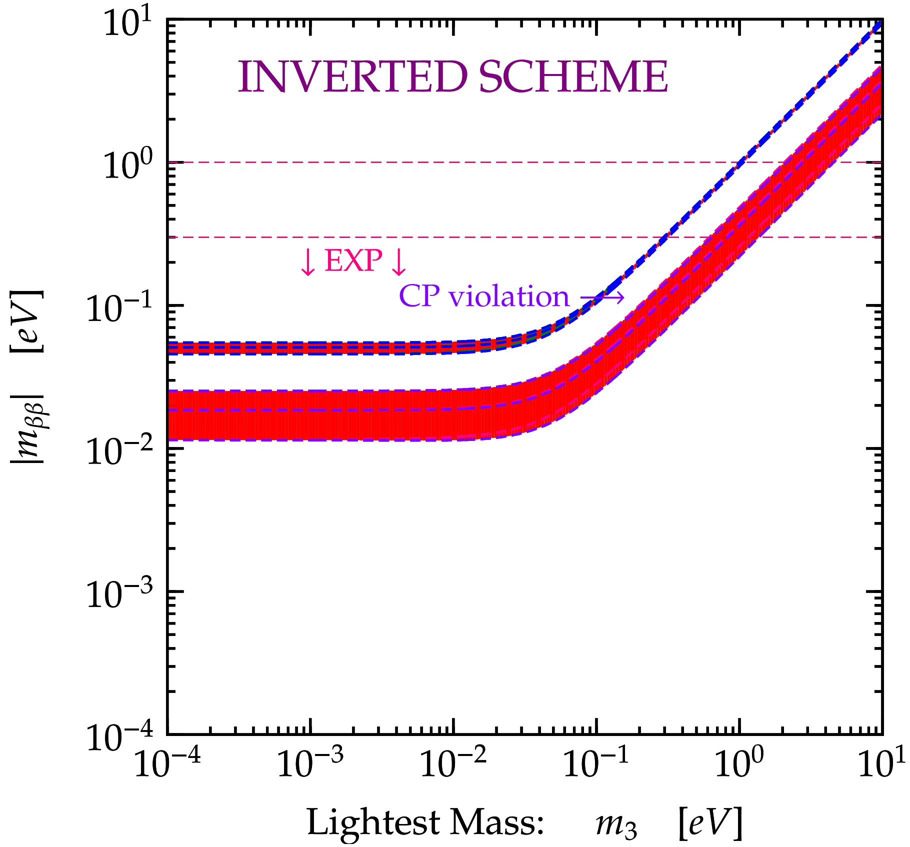
EXO, MOON, Super-NEMO, CUORE, Majorana, GEM, GERDA

$$|m_{\beta\beta}| \sim \text{few}\ 10^{-2}\,\text{eV}$$

Bounds from Neutrino Oscillations

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



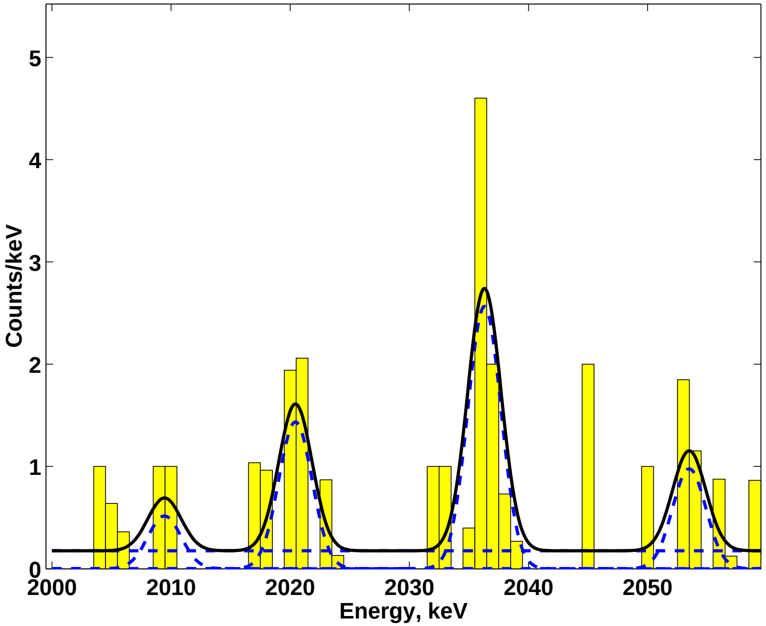


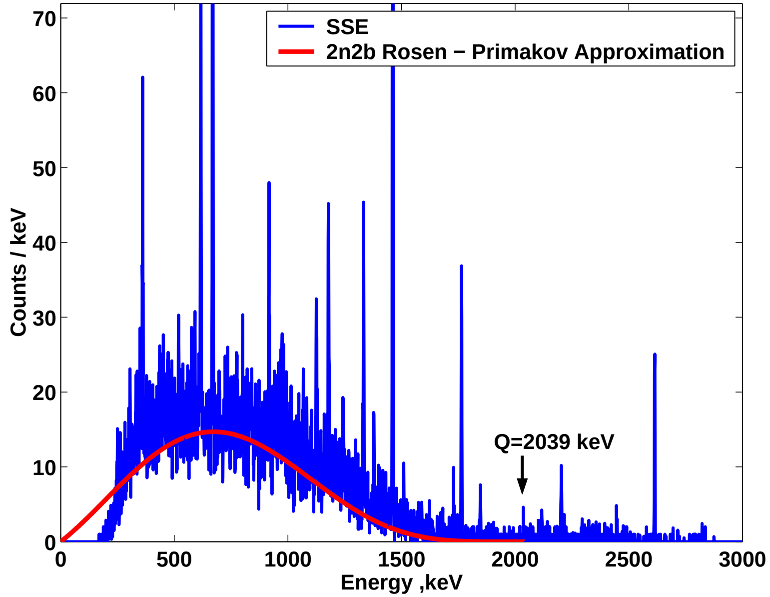
FUTURE: IF $|m_{\beta\beta}| \lesssim 10^{-2}$ eV $\Longrightarrow$ NORMAL HIERARCHY

Experimental Positive Indication

[Klapdor et al., MPLA 16 (2001) 2409; FP 32 (2002) 1181; NIMA 522 (2004) 371; PLB 586 (2004) 198]

$$T_{1/2}^{0\nu\,\mathrm{bf}} = 1.19 \times 10^{25}\,\mathrm{y} \qquad T_{1/2}^{0\nu} = (0.69 - 4.18) \times 10^{25}\,\mathrm{y}\,(3\sigma) \qquad 4.2\sigma\ \text{evidence}$$





pulse-shape selected spectrum

3.8σ evidence [PLB 586 (2004) 198]

the indication must be checked by other experiments

$$1.35 \lesssim |\mathcal{M}_{0\nu}| \lesssim 4.12 \quad \Longrightarrow \quad 0.22\,\mathrm{eV} \lesssim |m_{\beta\beta}| \lesssim 1.6\,\mathrm{eV}$$

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)

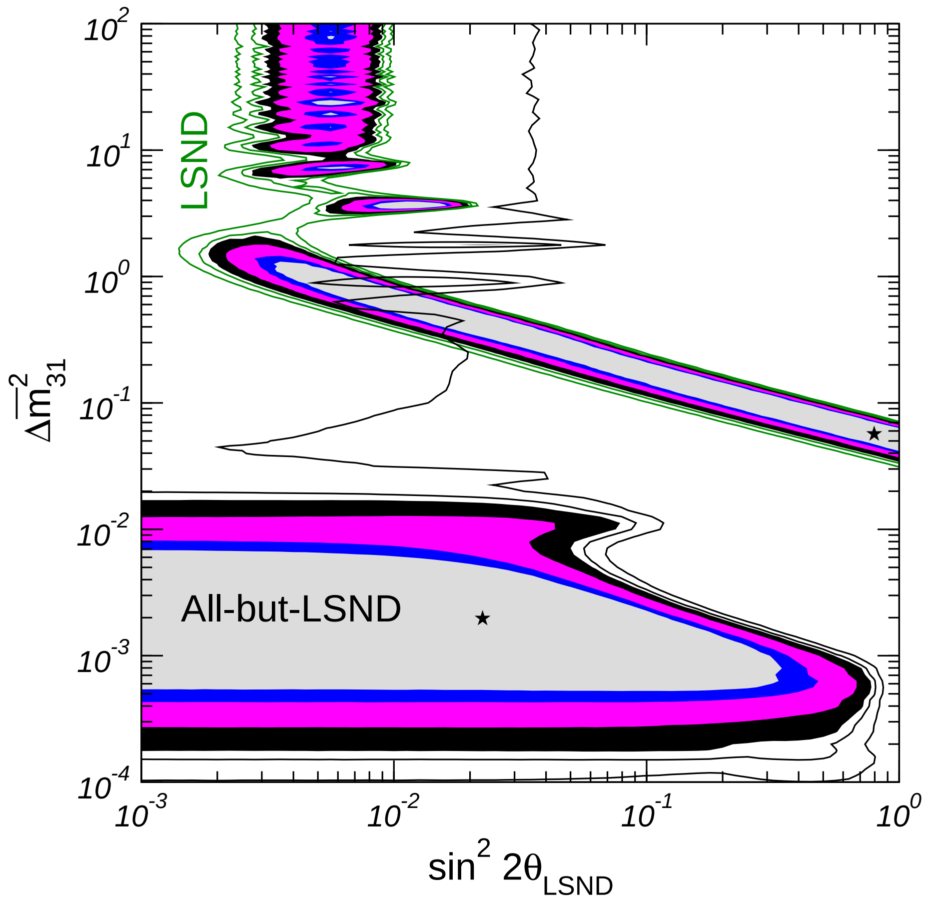
LSS (2dFGRS, SDSS)

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

$$\Lambda\text{CDM} \quad \Longrightarrow \quad \boxed{\sum_{k=1}^{3} m_k \lesssim 0.2 - 0.7\,\text{eV}}$$

LSND

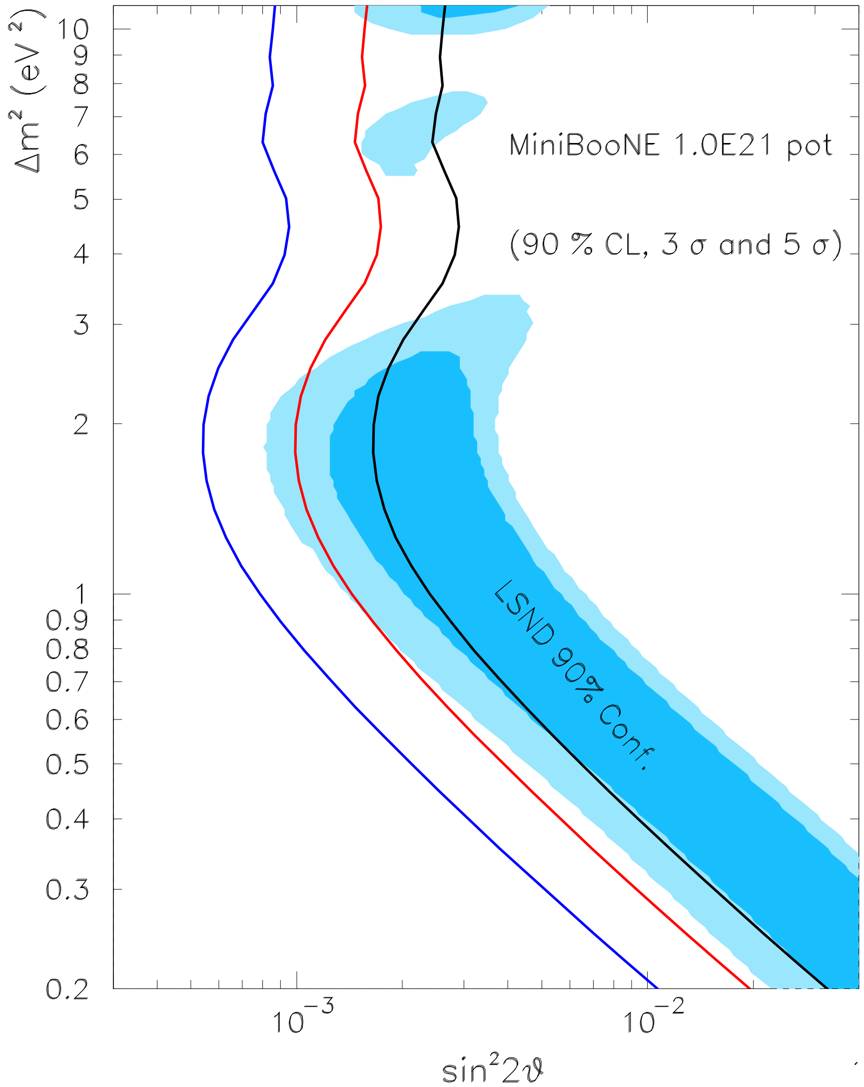
$\bar{\nu}_\mu \to \bar{\nu}_e$ $\Delta m^2_{\text{LSND}} \gtrsim 0.1\,\text{eV}^2$ $(\gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SUN}})$



[Gonzalez-Garcia, Maltoni, Schwetz PRD 68 (2003) 053007]

even allowing $\Delta\overline{m}^2_{31} \neq \Delta m^2_{31}$

(CPT violation) GoF $= 7.5 \times 10^{-4}$



MiniBooNE $\nu_\mu \to \nu_e$ [hep-ex/0406048]

Conclusions

$\nu_e \to \nu_\mu, \nu_\tau$ with $\Delta m^2_{\text{SUN}} \simeq 8.3 \times 10^{-5}\,\text{eV}^2$ (solar ν, KamLAND)

$\nu_\mu \to \nu_\tau$ with $\Delta m^2_{\text{ATM}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2$ (atm. ν, K2K, MINOS)

$\Downarrow$

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 $\mathcal{M}_{0\nu}$!

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