Phenomenology of Absolute ν Masses

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Introduction to Neutrino Masses, Mixing and Oscillations

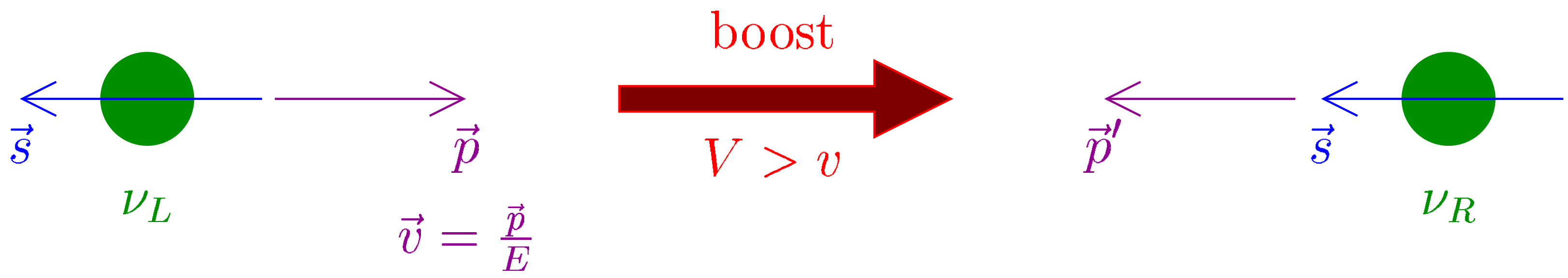
Solar $\nu_e \to \nu_\mu, \nu_\tau$ + Atmospheric $\nu_\mu \to \nu_\tau \Longrightarrow$ 3-ν Mixing

Absolute Scale of Neutrino Masses

Cosmological Bound on Neutrino Masses

Neutrinoless Double-β Decay $\Longleftrightarrow$ Majorana Mass

Neutrino Mass



Standard Model: $\nu_L, \nu_R^c \quad \Longrightarrow \quad$ no Dirac mass term $\quad \mathcal{L}^{\mathrm{D}} \sim m^{\mathrm{D}} \overline{\nu_L} \nu_R$

(no ν_R, ν_L^c)

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

$\nu_R^c \equiv \nu_R \quad \Longrightarrow \quad$ Majorana mass term $\quad \mathcal{L}^{\mathrm{M}} \sim m^{\mathrm{M}} \overline{\nu_L} \nu_R^c$

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

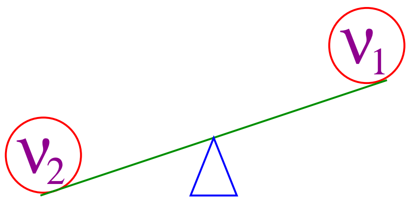
surprise: Majorana neutrino mass for ν_R is allowed! $\quad \mathcal{L}^{\text{M}}_R \sim m^{\text{M}}_R \overline{\nu^c_L} \nu_R$

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

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

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

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



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

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

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

Diagonalization of Mass Matrix: Mixing

Dirac Mass Term: $\mathcal{L}^{\mathrm{D}} \sim \begin{pmatrix} \overline{\nu_{eL}} & \overline{\nu_{\mu L}} & \overline{\nu_{\tau L}} \end{pmatrix} \begin{pmatrix} m^{\mathrm{D}}_{ee} & m^{\mathrm{D}}_{e\mu} & m^{\mathrm{D}}_{e\tau} \\ m^{\mathrm{D}}_{\mu e} & m^{\mathrm{D}}_{\mu\mu} & m^{\mathrm{D}}_{\mu\tau} \\ m^{\mathrm{D}}_{\tau e} & m^{\mathrm{D}}_{\tau\mu} & m^{\mathrm{D}}_{\tau\tau} \end{pmatrix} \begin{pmatrix} \nu_{eR} \\ \nu_{\mu R} \\ \nu_{\tau R} \end{pmatrix}$

$$\mathcal{L}^{\mathrm{D}} \sim \sum_{\alpha,\beta} \overline{\nu_{\alpha L}} m^{\mathrm{D}}_{\alpha\beta} \nu_{\beta R} \qquad (\alpha, \beta = e, \mu, \tau)$$

$$\nu_{\alpha L} = \sum_{k=1}^{3} U_{\alpha k} \nu_{kL} \qquad \nu_{\beta R} = \sum_{j=1}^{3} V_{\beta j} \nu_{jR} \qquad U^{\dagger} m^{\mathrm{D}} V = \mathrm{diag}(m_1, m_2, m_3)$$

$$\mathcal{L}^{\mathrm{D}} \sim \sum_{k=1}^{3} m_k \overline{\nu_{kL}} \nu_{kR}$$

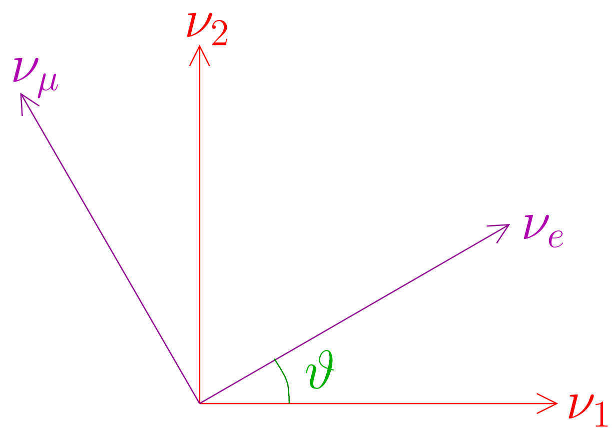
Weak Charged Current: neutrino production and detection

$$j^{\mathrm{CC}}_{\rho} \sim \sum_{\alpha=e,\mu,\tau} \overline{\ell_{\alpha L}} \gamma_{\rho} \nu_{\alpha L} = \sum_{\alpha=e,\mu,\tau} \sum_{k=1}^{3} \overline{\ell_{\alpha L}} \gamma_{\rho} U_{\alpha k} \nu_{kL}$$

$$U = \text{unitary } 3 \times 3 \text{ mixing matrix}$$

Two-Neutrino Mixing and Oscillations

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



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

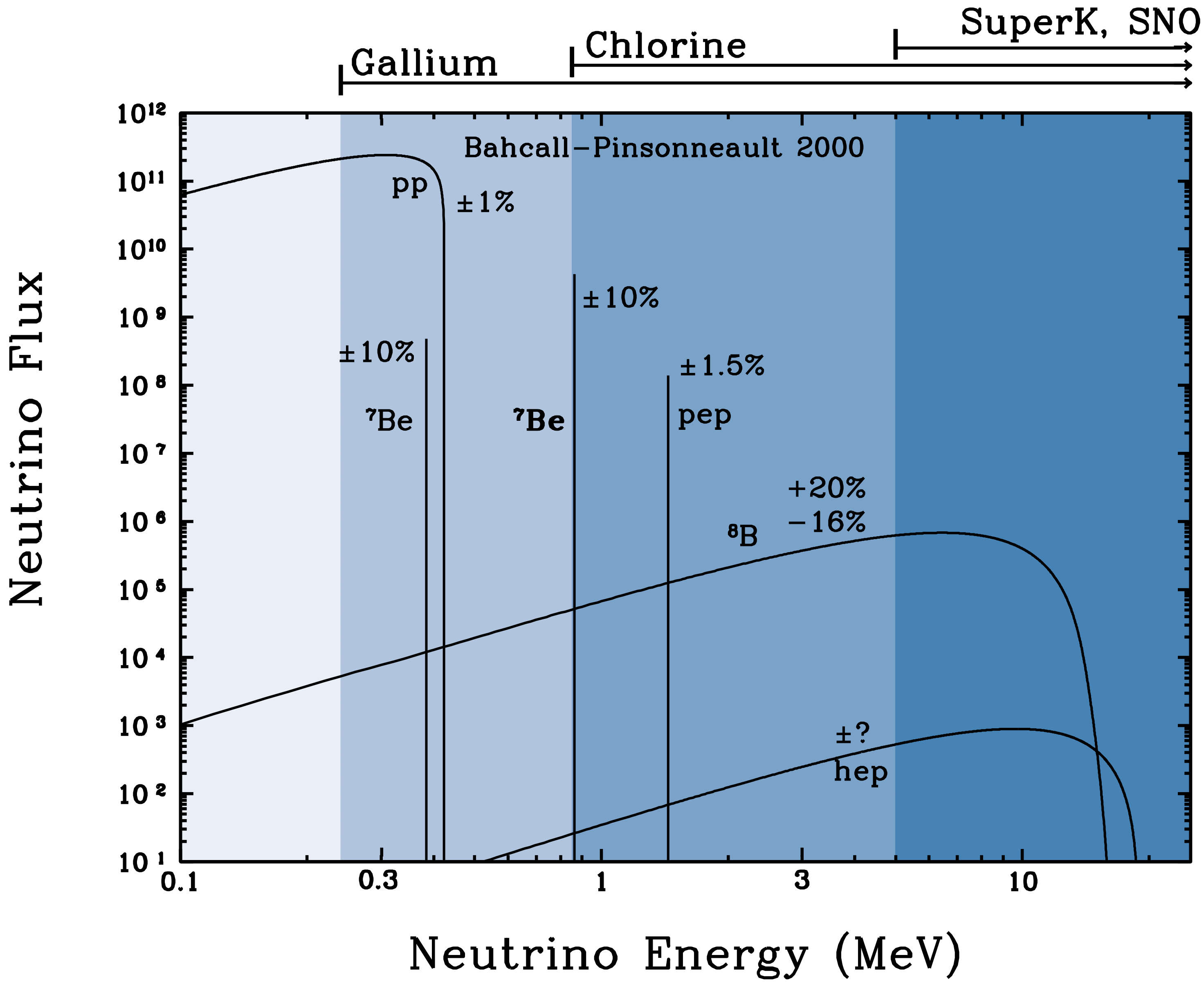
$$\boxed{\begin{aligned} |\nu_e\rangle &= \cos\vartheta\,|\nu_1\rangle + \sin\vartheta\,|\nu_2\rangle \\ |\nu_\mu\rangle &= -\sin\vartheta\,|\nu_1\rangle + \cos\vartheta\,|\nu_2\rangle \end{aligned}}$$

$$\Delta m^2 \equiv \Delta m^2_{21} \equiv m_2^2 - m_1^2$$

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]

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

$$\Phi^{\rm SNO}_{\nu_\mu,\nu_\tau} = 5.41 \pm 0.66 \times 10^6 \, {\rm cm}^{-2} \, {\rm s}^{-1}$$

SNO solved
solar neutrino problem

$\Downarrow$

Neutrino Physics
(April 2002)

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

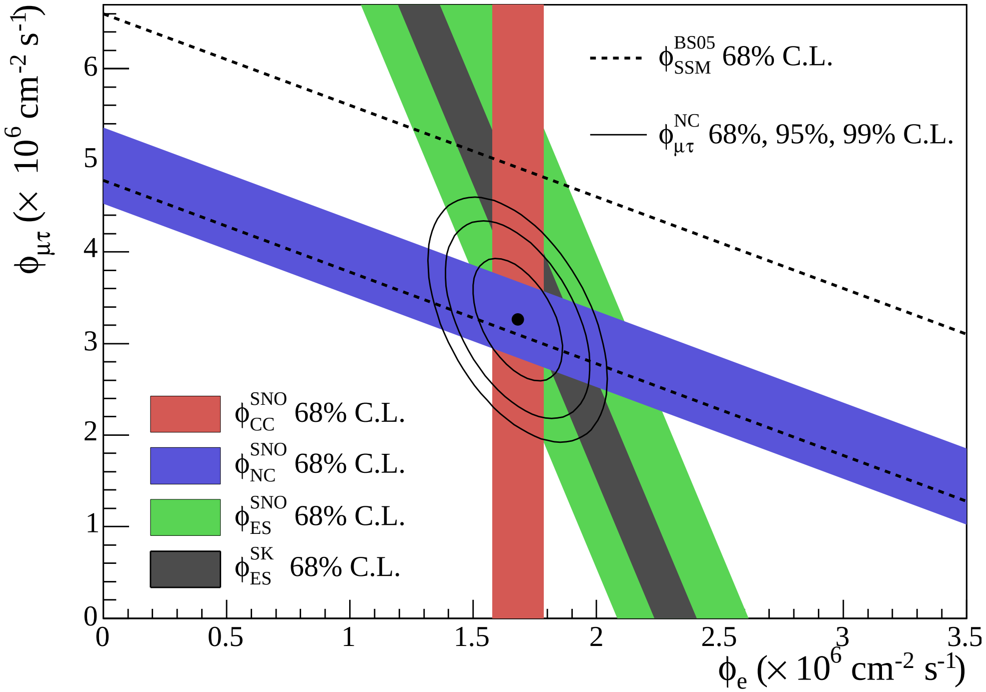
$\nu_e \to \nu_\mu, \nu_\tau$ oscillations

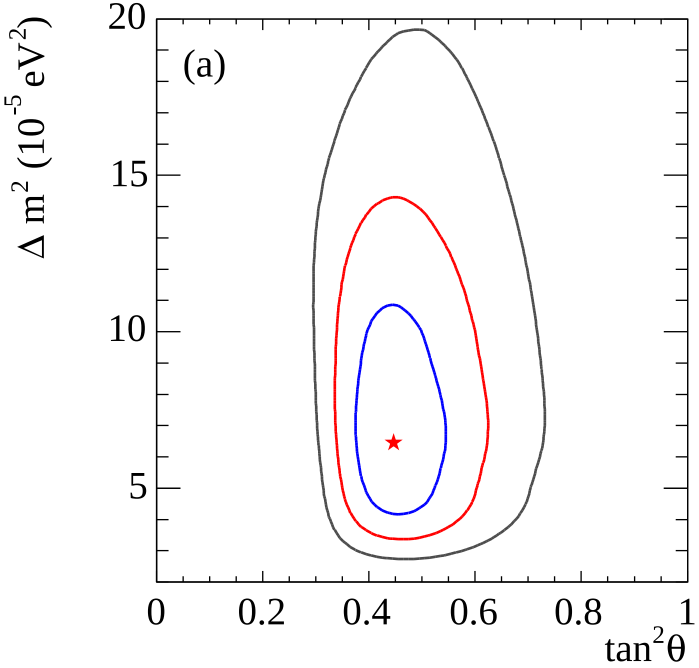
$\Downarrow$

Large Mixing Angle solution

$$\Delta m^2 \simeq 7 \times 10^{-5} \, {\rm eV}^2$$

$$\tan^2 \vartheta \simeq 0.45$$

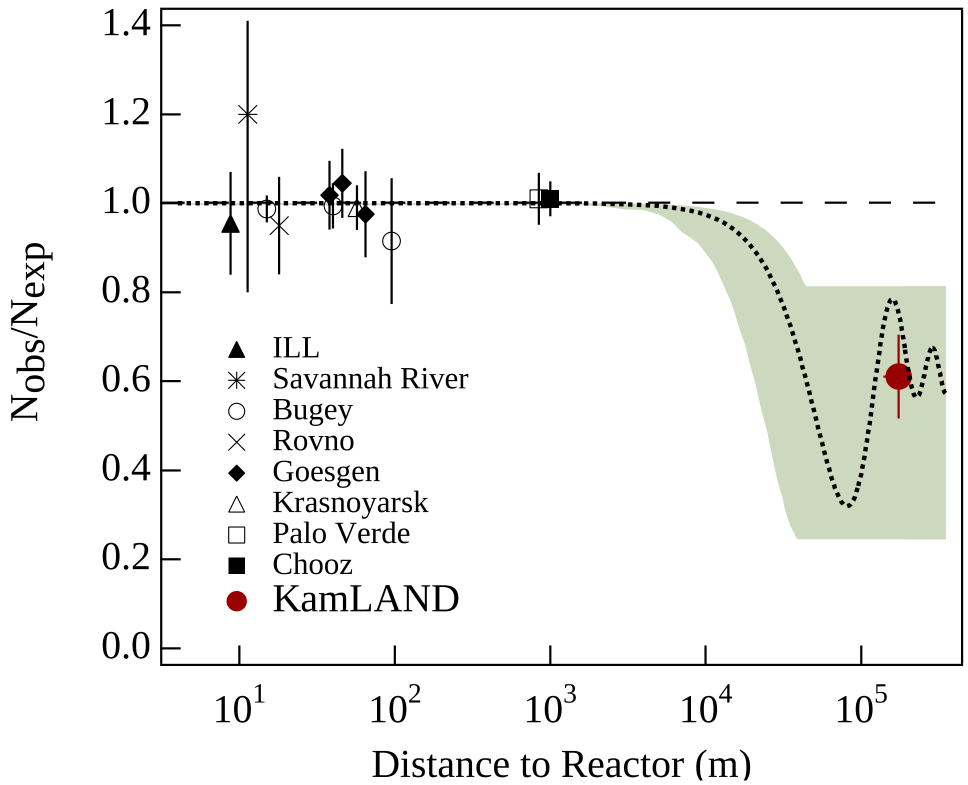




[SNO, PRC 72 (2005) 055502, nucl-ex/0502021]

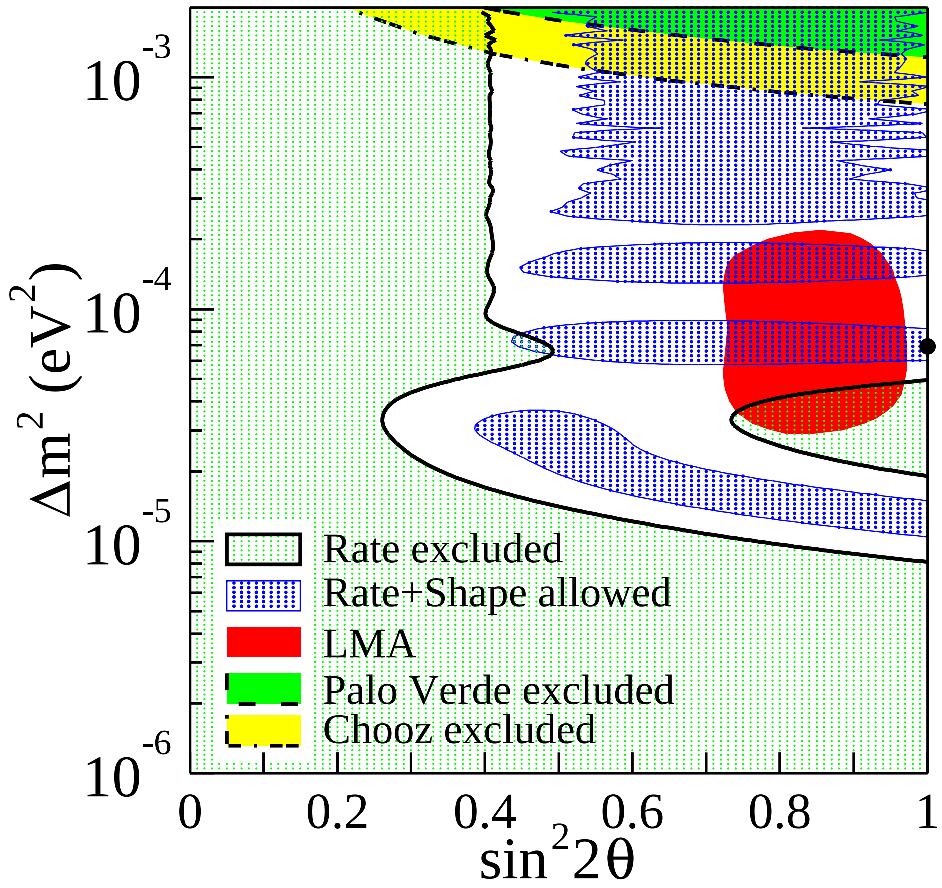
KamLAND

confirmation of LMA (December 2002)



Shade: 95% C.L. LMA

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

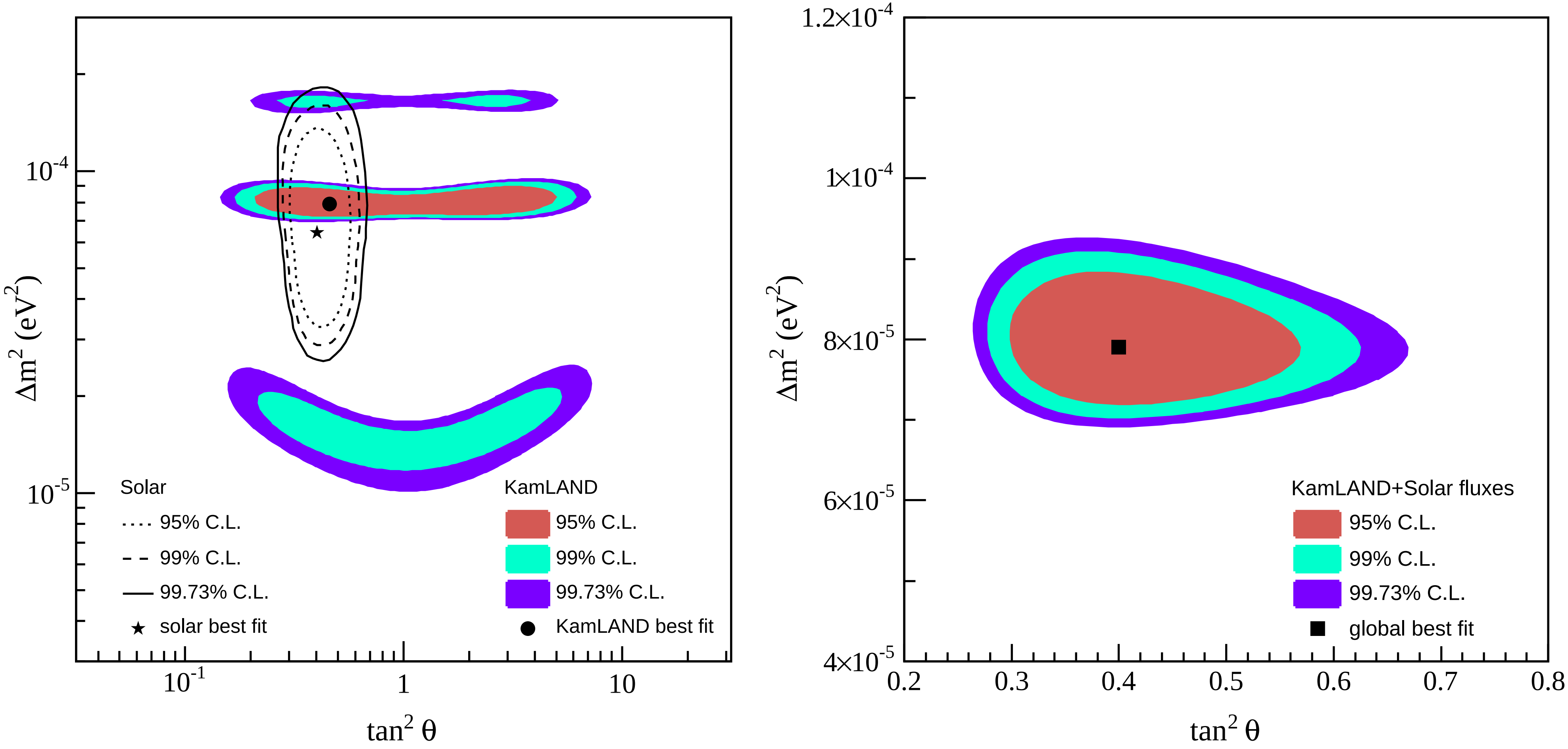


95% C.L.

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

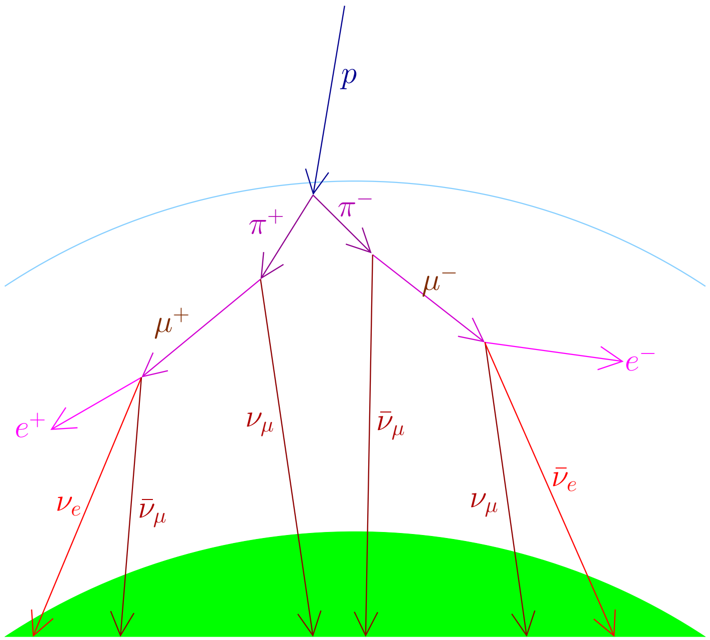
Combined Fit of Solar and Reactor Neutrino Data

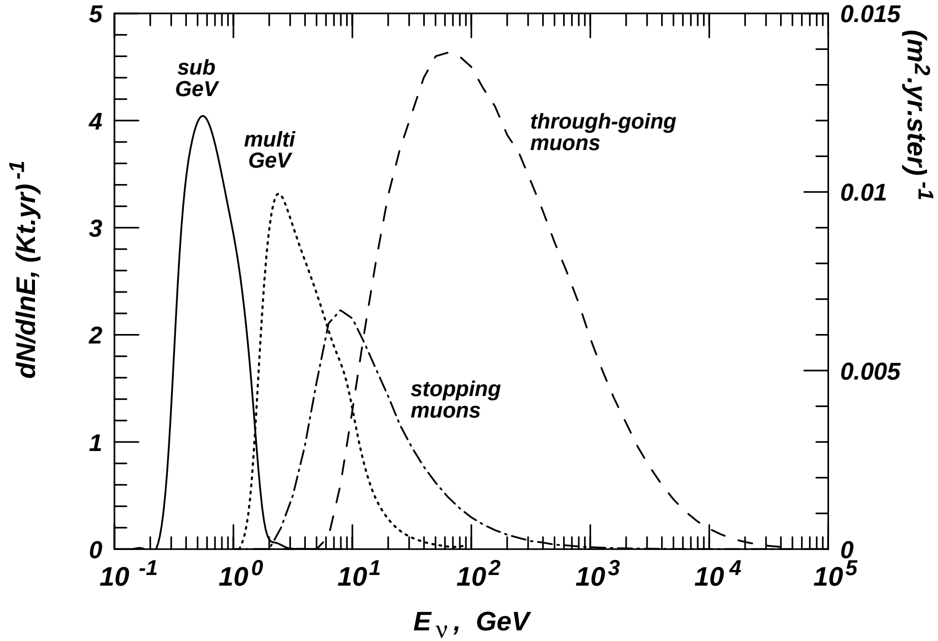
[KamLAND, hep-ex/0406035]



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





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

uncertainty on ratios: $\sim 5\%$

uncertainty on fluxes: $\sim 30\%$

ratio of ratios

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

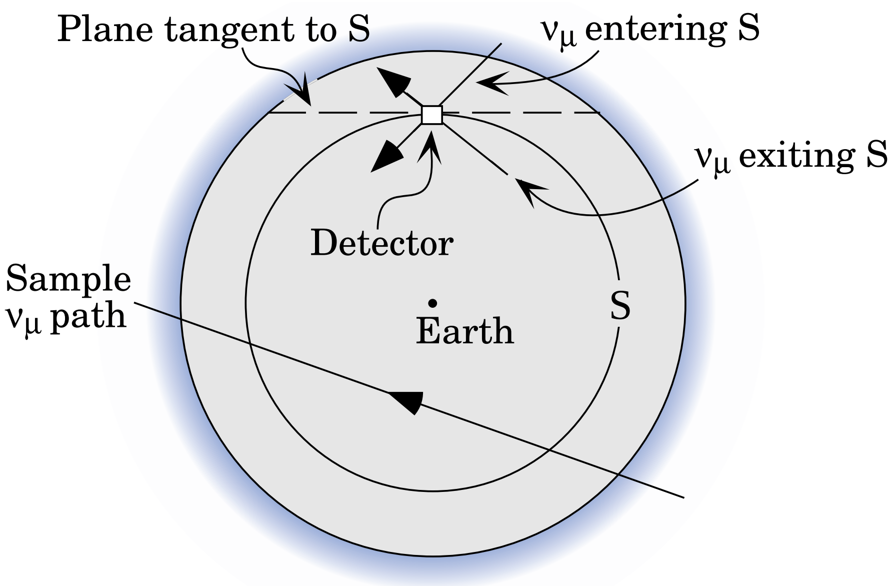
$$R^{\text{K}}_{\text{sub-GeV}} = 0.60 \pm 0.07 \pm 0.05$$

[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]

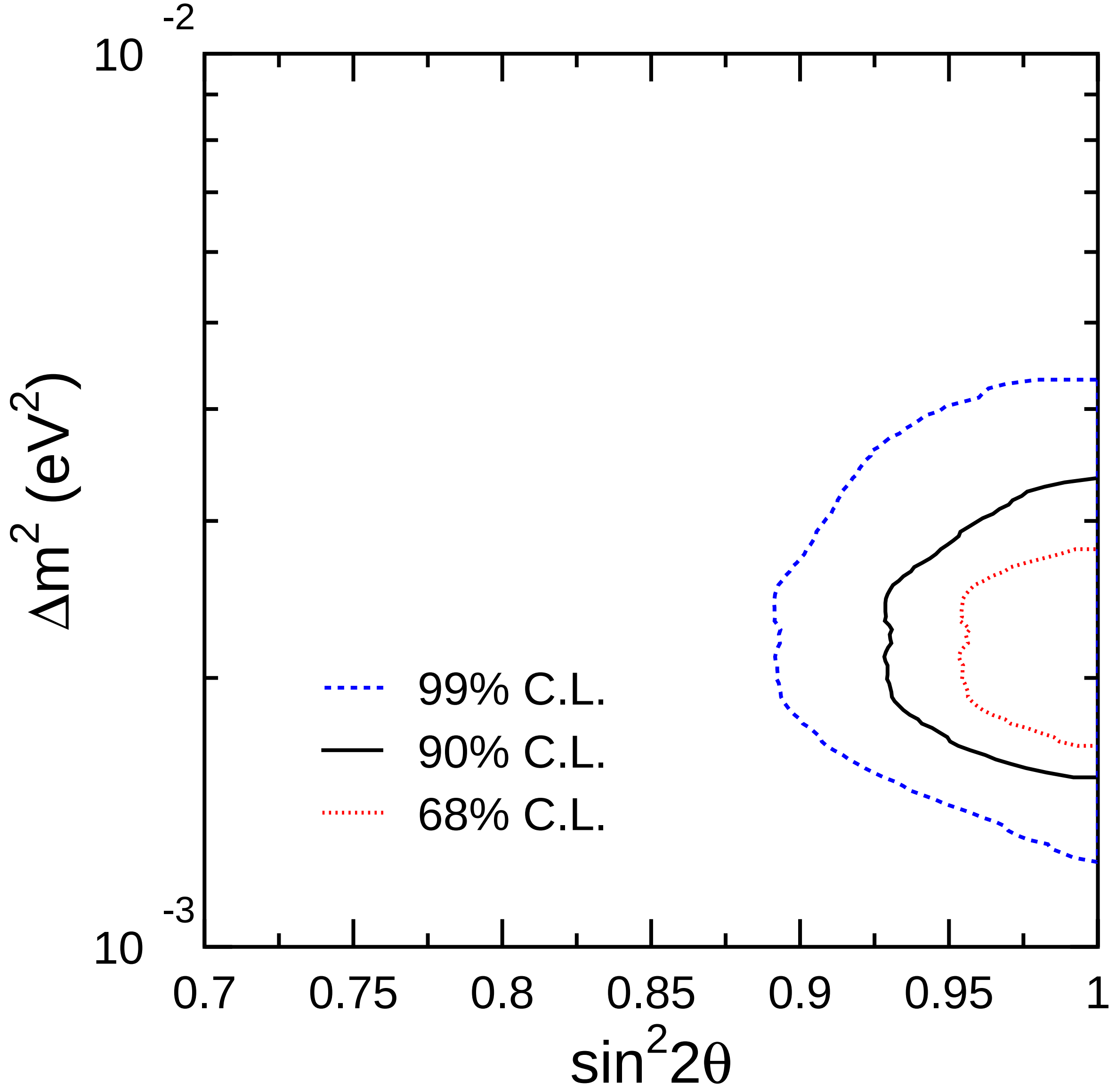
(December 1998)

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

[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

$\Delta m^2 = 2.1 \times 10^{-3}\,\text{eV}^2$

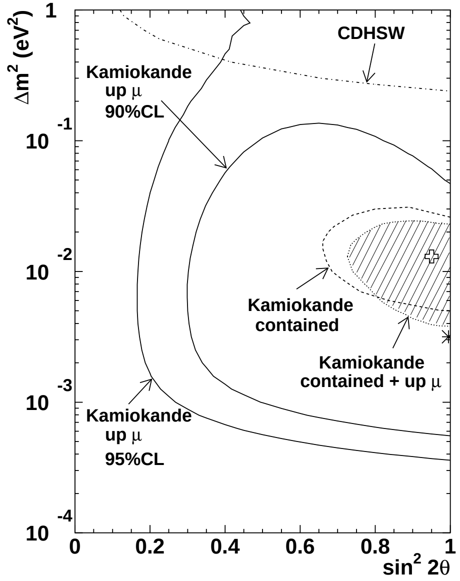
$\sin^2 2\theta = 1.0$

1489 live-days

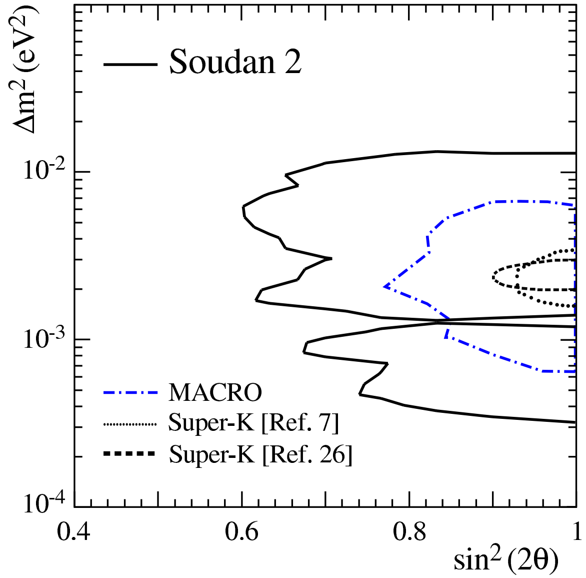
April 1996 – July 2001

[Super-Kamiokande, hep-ex/0501064]

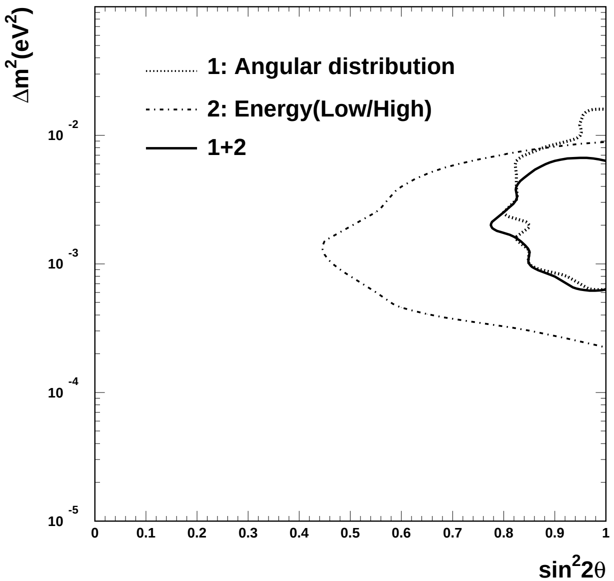
Kamiokande, Soudan-2, MACRO and MINOS



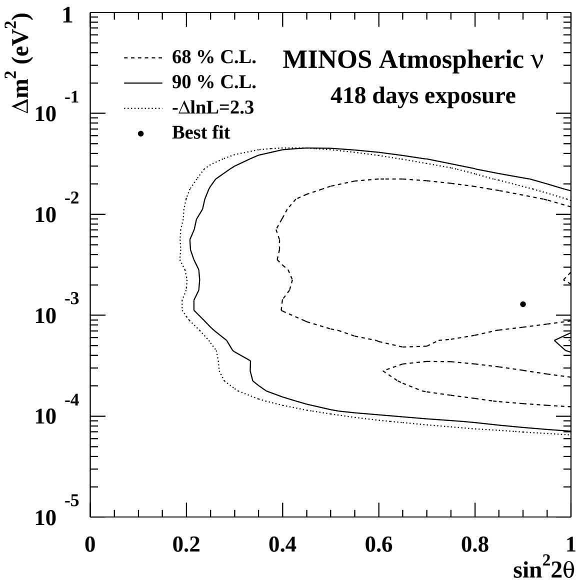
[Kamiokande, hep-ex/9806038]



[Soudan 2, hep-ex/0507068]



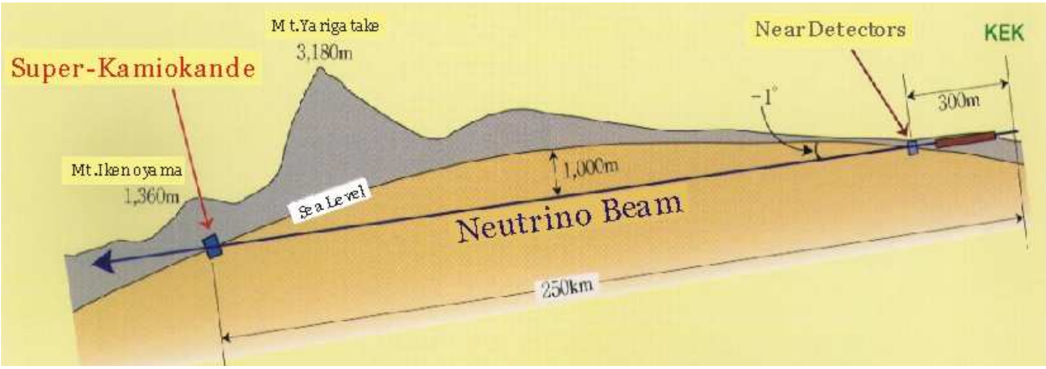
[MACRO, hep-ex/0304037]



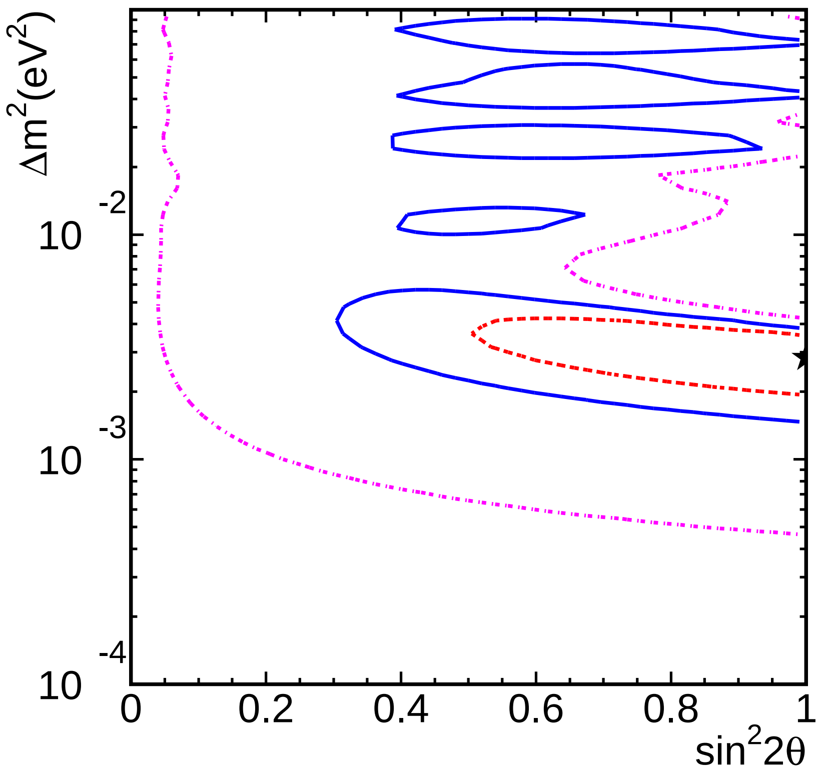
[MINOS, hep-ex/0512036]

K2K

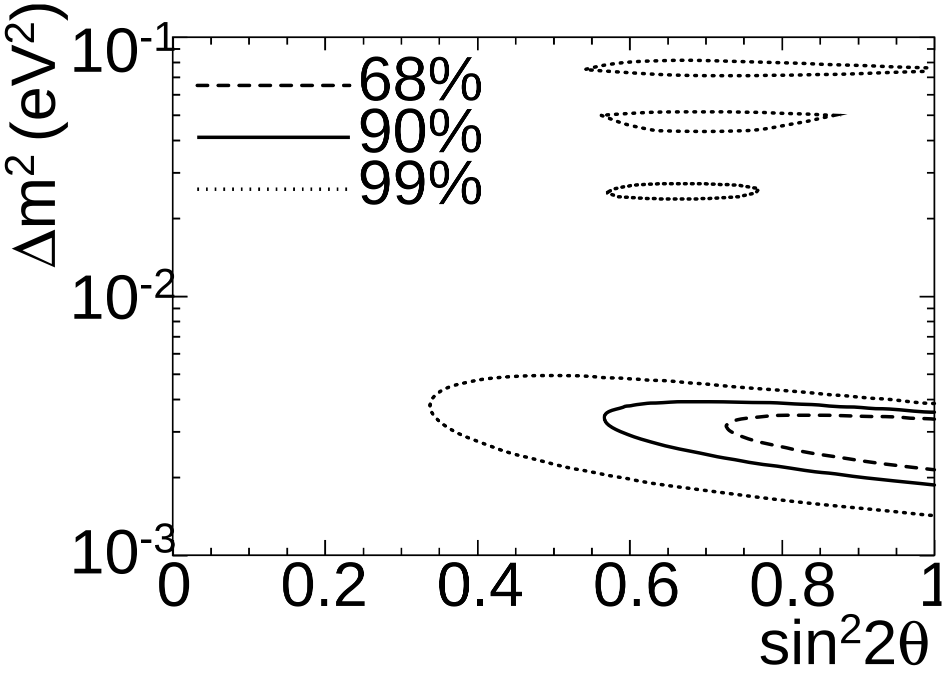
confirmation of atmospheric allowed region (June 2002)



KEK to Kamioka
(Super-Kamiokande)
250 km



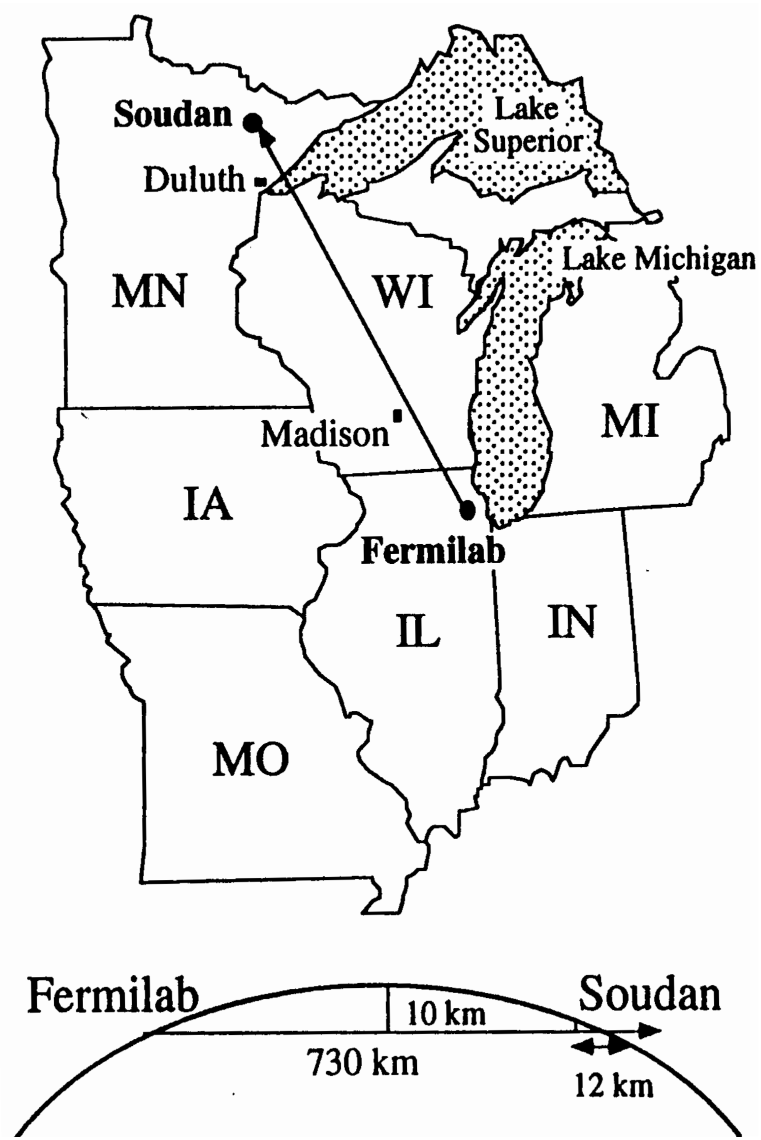
[K2K, Phys. Rev. Lett. 90 (2003) 041801]

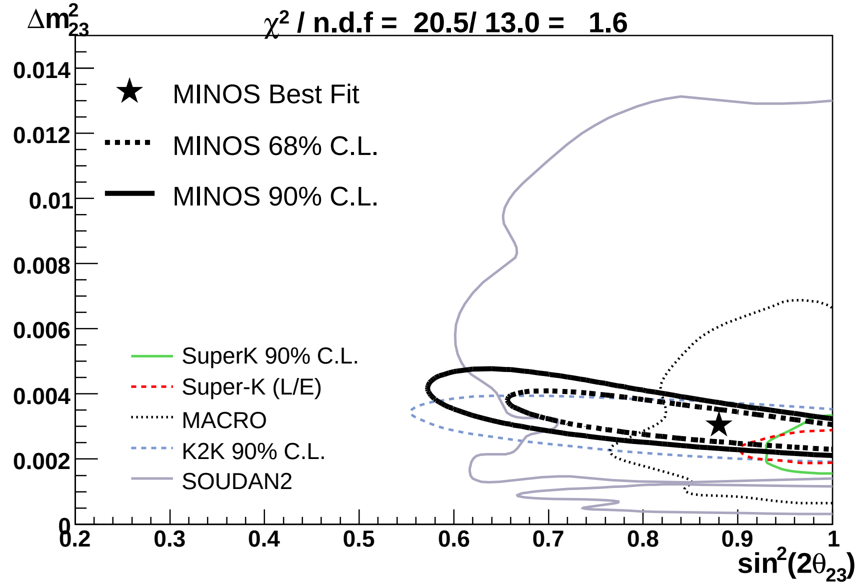


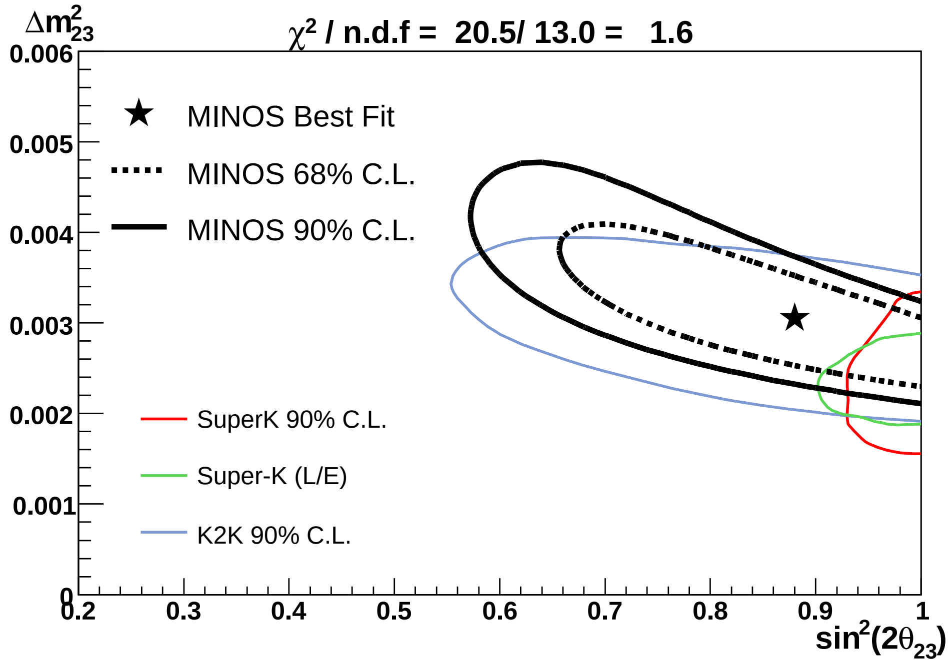
[K2K, hep-ex/0411038]

MINOS

30 March 2006 http://www-numi.fnal.gov/







Experimental Evidences of Neutrino Oscillations

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

Reactor
$\bar{\nu}_e$ disappearance

$\left(\begin{array}{c} \text{Homestake} \\ \text{Kamiokande} \\ \text{GALLEX/GNO} \\ \text{SAGE} \\ \text{Super-Kamiokande} \end{array} \right)$

(KamLAND)

$$\Longrightarrow \begin{cases} \Delta m^2_{\text{SUN}} = 7.92\,(1 \pm 0.09) \times 10^{-5}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{SUN}} = 0.314\,\left(1^{+0.18}_{-0.15}\right) \end{cases}$$

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

Accelerator
ν_μ disappearance

$\left(\begin{array}{c} \text{Kamiokande} \\ \text{IMB} \\ \text{Super-Kamiokande} \\ \text{MACRO} \\ \text{Soudan-2} \end{array} \right)$

(K2K & MINOS)

$$\Longrightarrow \begin{cases} \Delta m^2_{\text{ATM}} = 2.4\,\left(1^{+0.21}_{-0.26}\right) \times 10^{-3}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{ATM}} = 0.44\,\left(1^{+0.41}_{-0.22}\right) \end{cases}$$

[Fogli, Lisi, Marrone, Palazzo. hep-ph/0506083]

Three-Neutrino Mixing

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

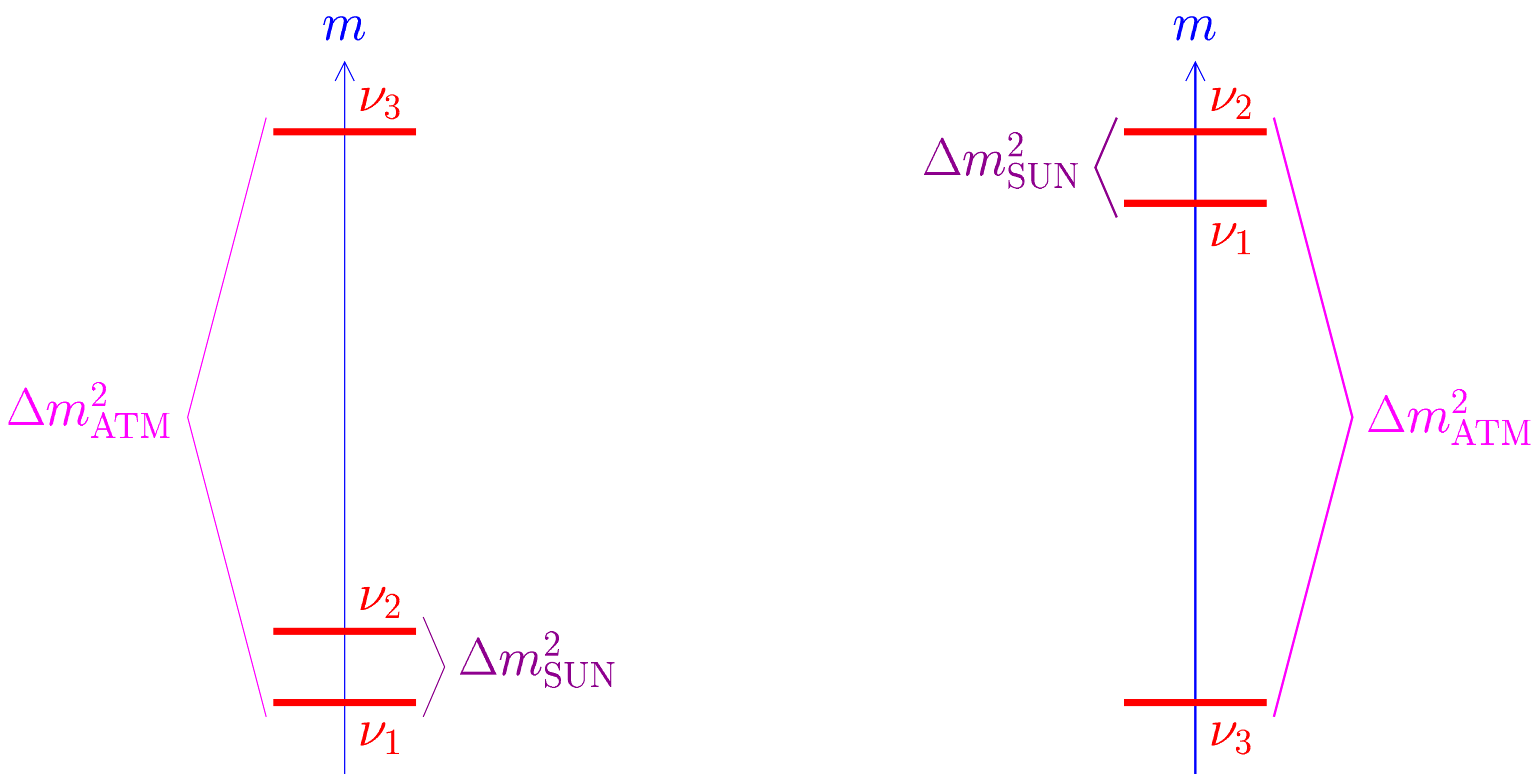
three flavor fields ν_e, ν_μ, ν_τ

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"

absolute scale is not determined by neutrino oscillation data

Standard Parameterization of Mixing Matrix

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

$$U = R_{23} \, W_{13} \, R_{12}$$

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

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

Global Fit of Oscillation Data: Bilarge Mixing

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

$$\Delta m^2_{\text{ATM}} = 2.4\left(1^{+0.21}_{-0.26}\right) \times 10^{-3}\,\text{eV}^2 \qquad \sin^2\vartheta_{\text{ATM}} = 0.44\left(1^{+0.41}_{-0.22}\right)$$

$$\sin^2\vartheta_{\text{CHOOZ}} = 0.9^{+2.3}_{-0.9} \times 10^{-2}$$

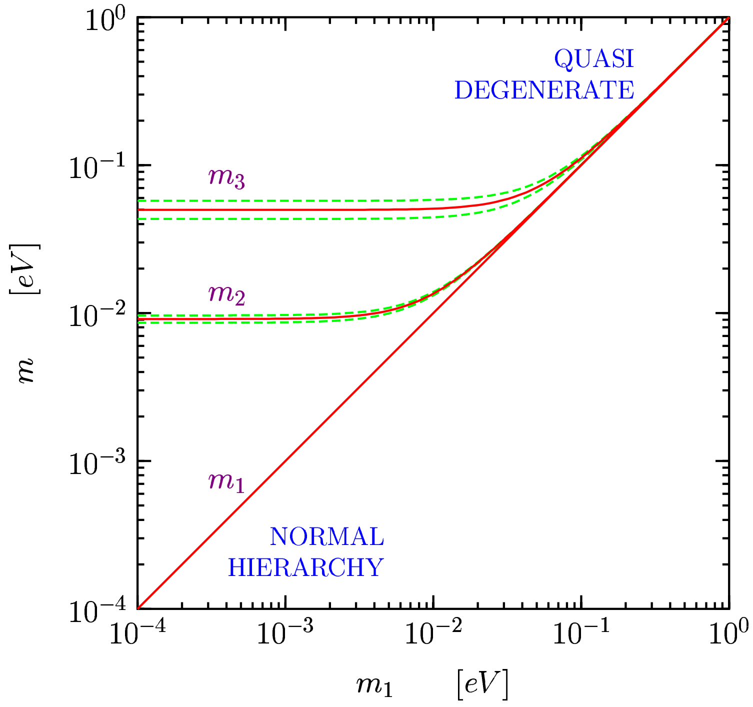
[Fogli, Lisi, Marrone, Palazzo. hep-ph/0506083]

$$|U|_{\text{bf}} \simeq \begin{pmatrix} 0.82 & 0.56 & 0.09 \\ 0.31-0.43 & 0.51-0.59 & 0.75 \\ 0.37-0.47 & 0.59-0.66 & 0.66 \end{pmatrix}$$

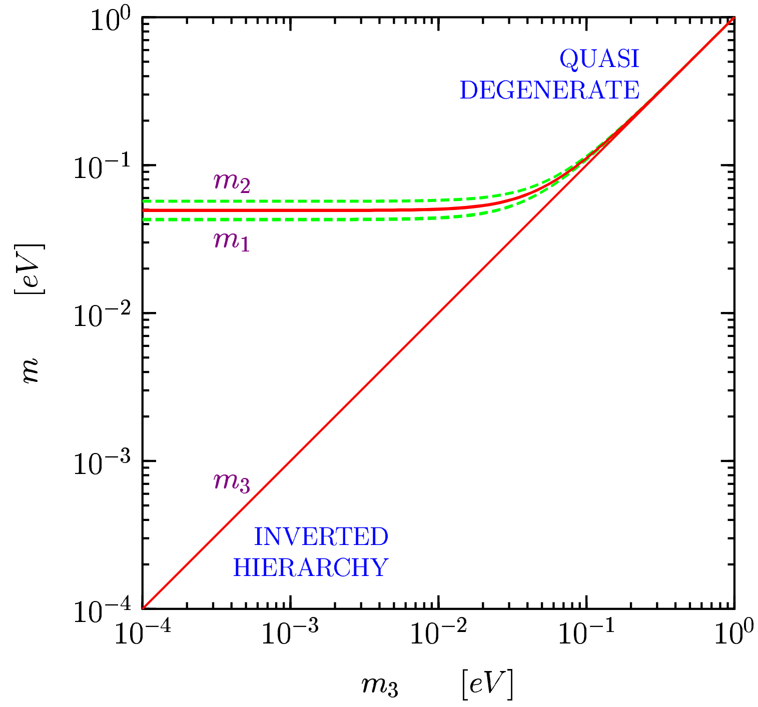
$$|U|_{3\sigma} \simeq \begin{pmatrix} 0.78-0.86 & 0.51-0.61 & 0.00-0.18 \\ 0.19-0.57 & 0.39-0.73 & 0.61-0.80 \\ 0.20-0.57 & 0.40-0.74 & 0.59-0.79 \end{pmatrix}$$

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

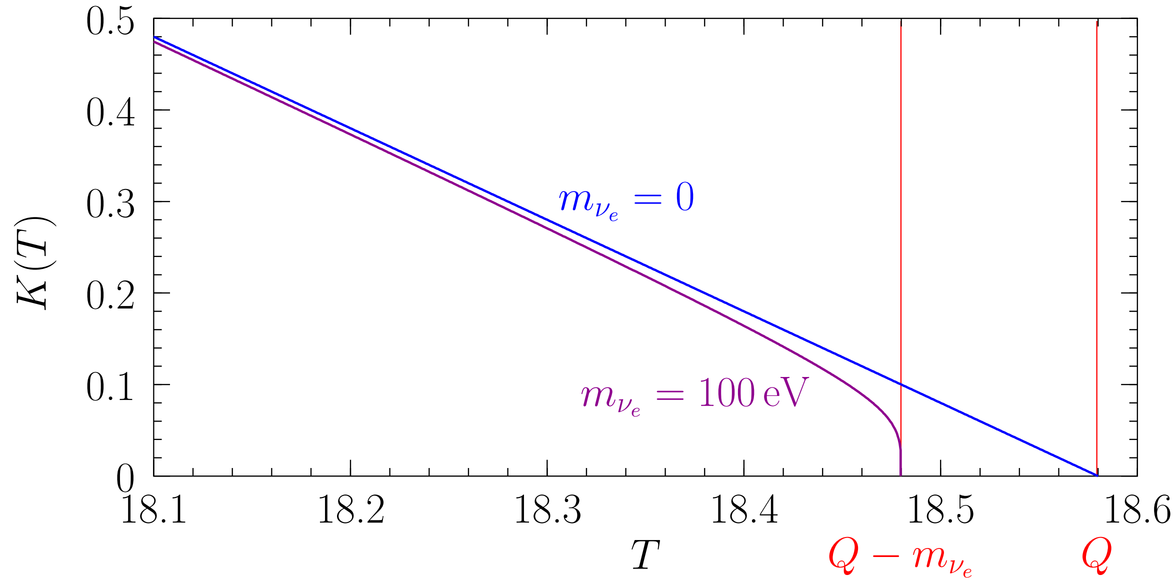
$^{3}\mathrm{H} \to {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$

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

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

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

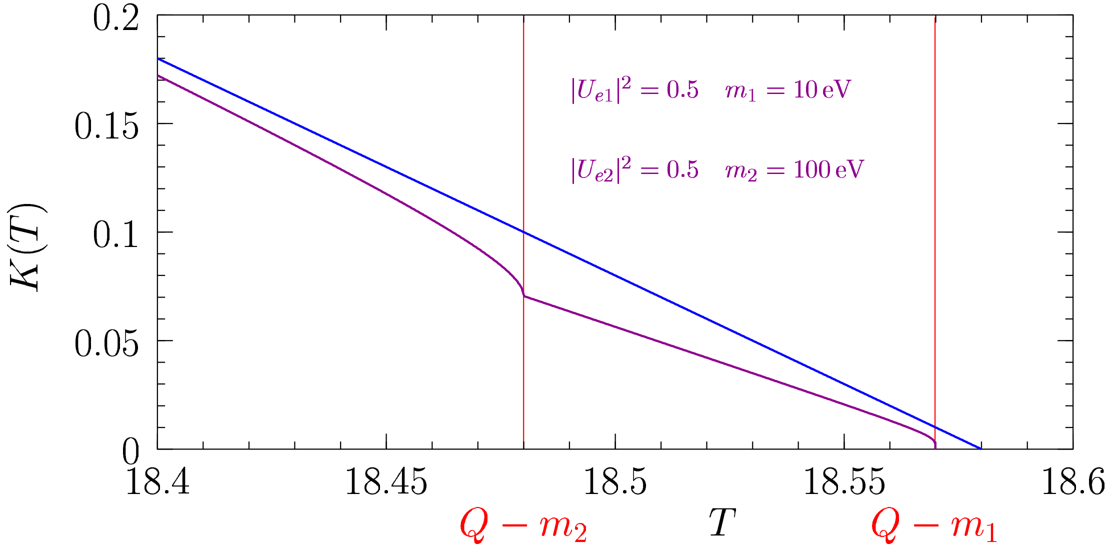
[Weinheimer, hep-ex/0210050]

future: KATRIN

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

sensitivity: $m_{\nu_e} \simeq 0.2 - 0.3\,\mathrm{eV}$

Neutrino Mixing $\Longrightarrow K(T) = \left[(Q-T)\sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2}\right]^{1/2}$



analysis of data is different from the no-mixing case: $2N-1$ parameters $\left(\sum_k |U_{ek}|^2 = 1\right)$

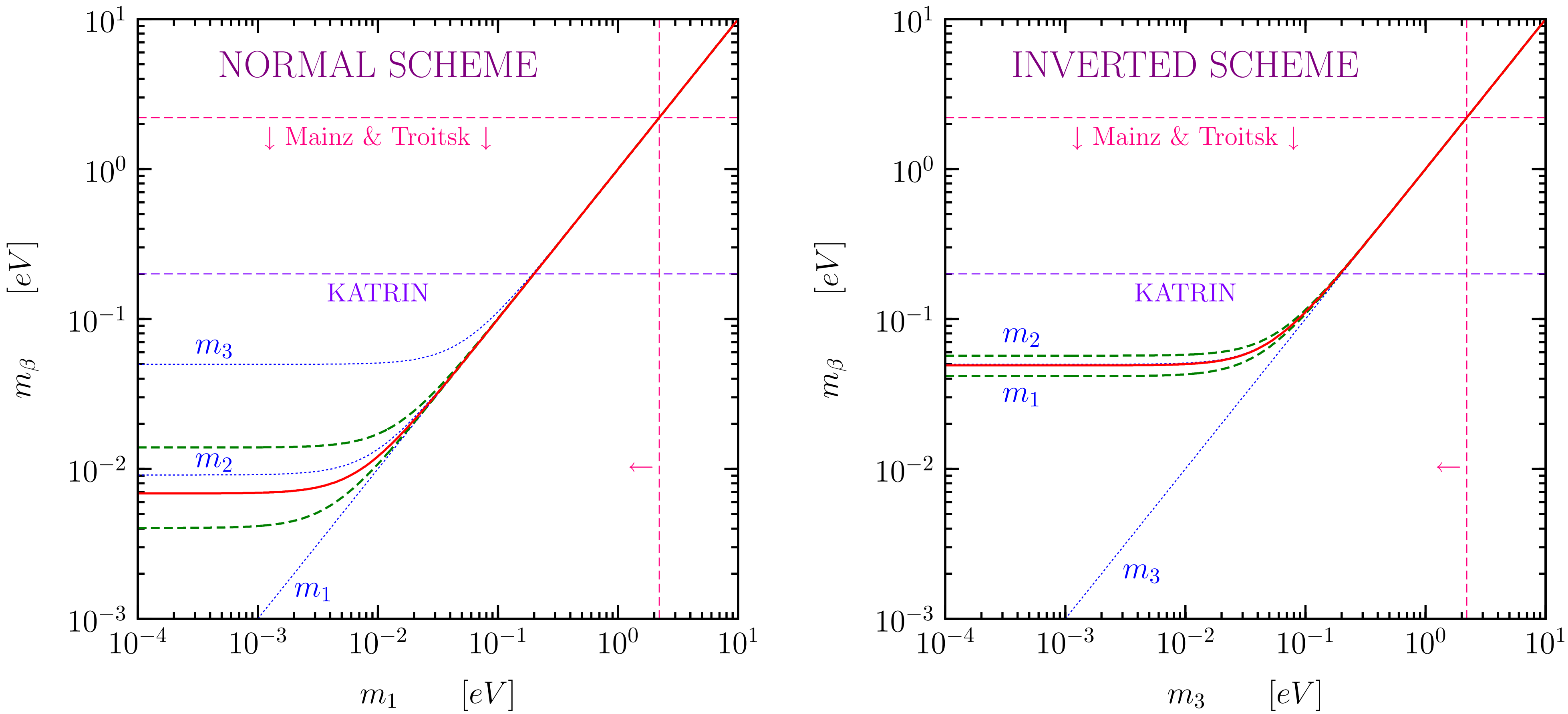
if experiment is not sensitive to masses $(m_k \ll Q - T)$

effective mass: $\boxed{m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2}$

$$K^2 = (Q-T)^2 \sum_k |U_{ek}|^2 \sqrt{1 - \frac{m_k^2}{(Q-T)^2}} \simeq (Q-T)^2 \sum_k |U_{ek}|^2 \left[1 - \frac{1}{2}\frac{m_k^2}{(Q-T)^2}\right]$$

$$= (Q-T)^2 \left[1 - \frac{1}{2}\frac{m_\beta^2}{(Q-T)^2}\right] \simeq (Q-T)\sqrt{(Q-T)^2 - m_\beta^2}$$

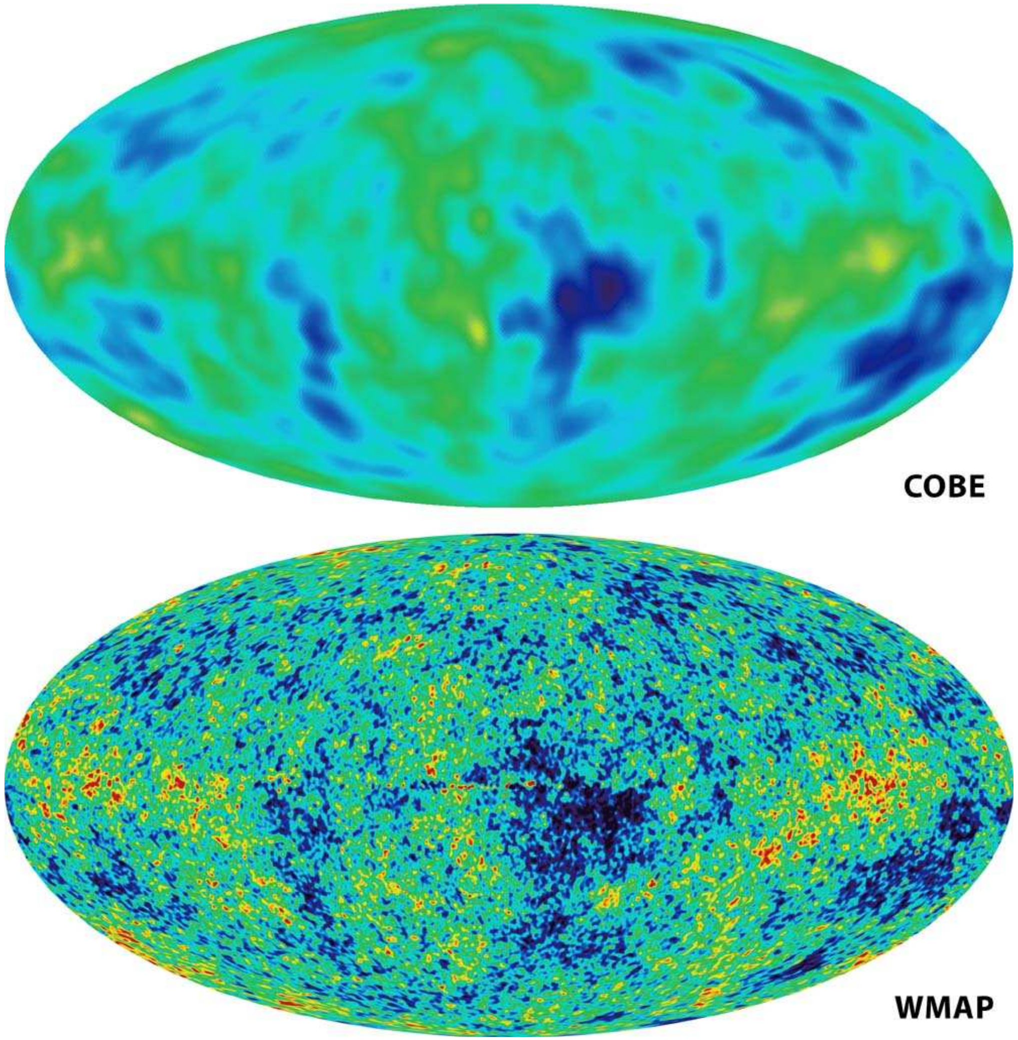
$$m_\beta^2 = |U_{e1}|^2\, m_1^2 + |U_{e2}|^2\, m_2^2 + |U_{e3}|^2\, m_3^2$$



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

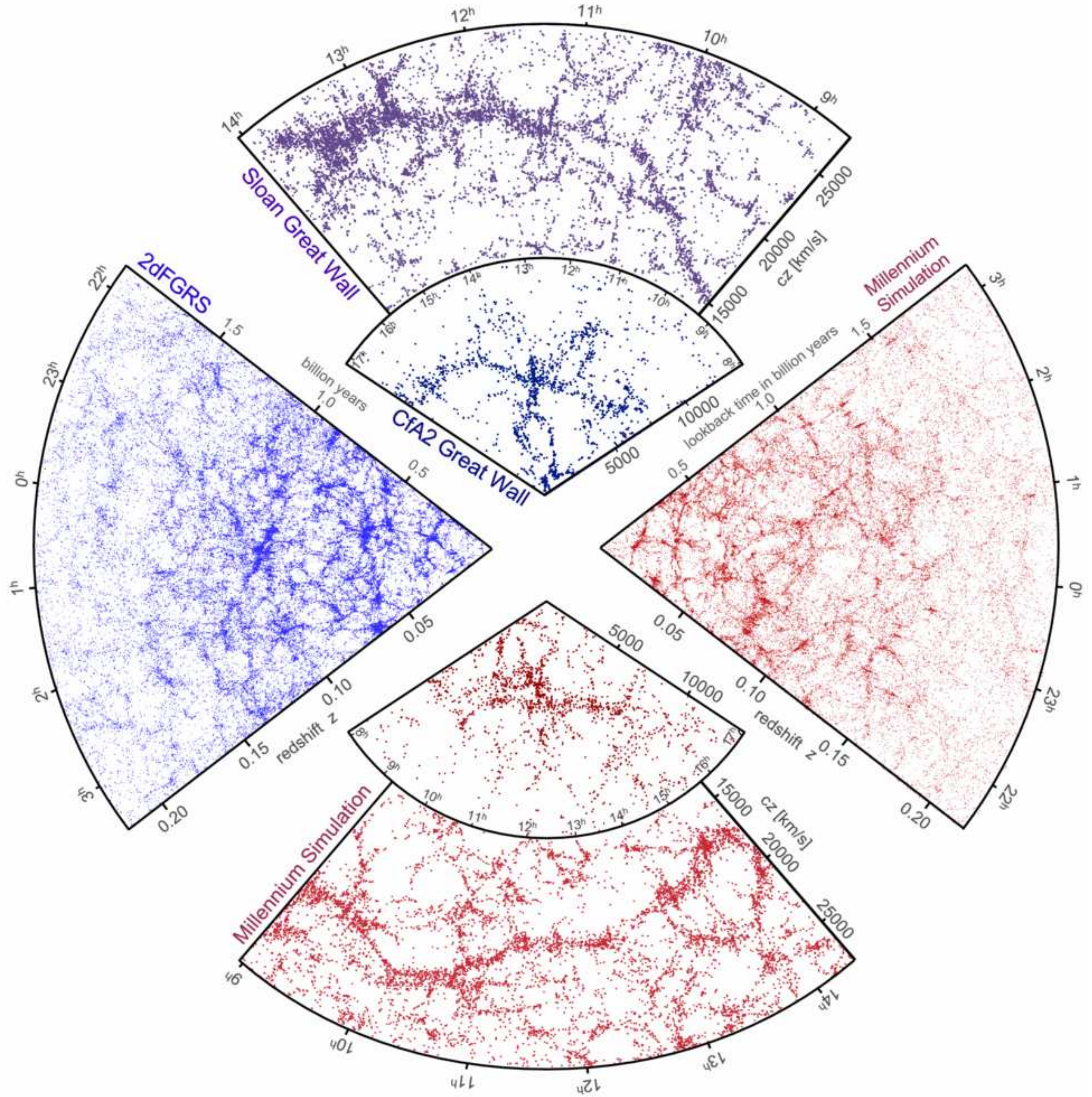
FUTURE: IF $m_\beta \lesssim 4 \times 10^{-2}\,\text{eV} \implies$ NORMAL HIERARCHY

WMAP (Wilkinson Microwave Anisotropy Probe)



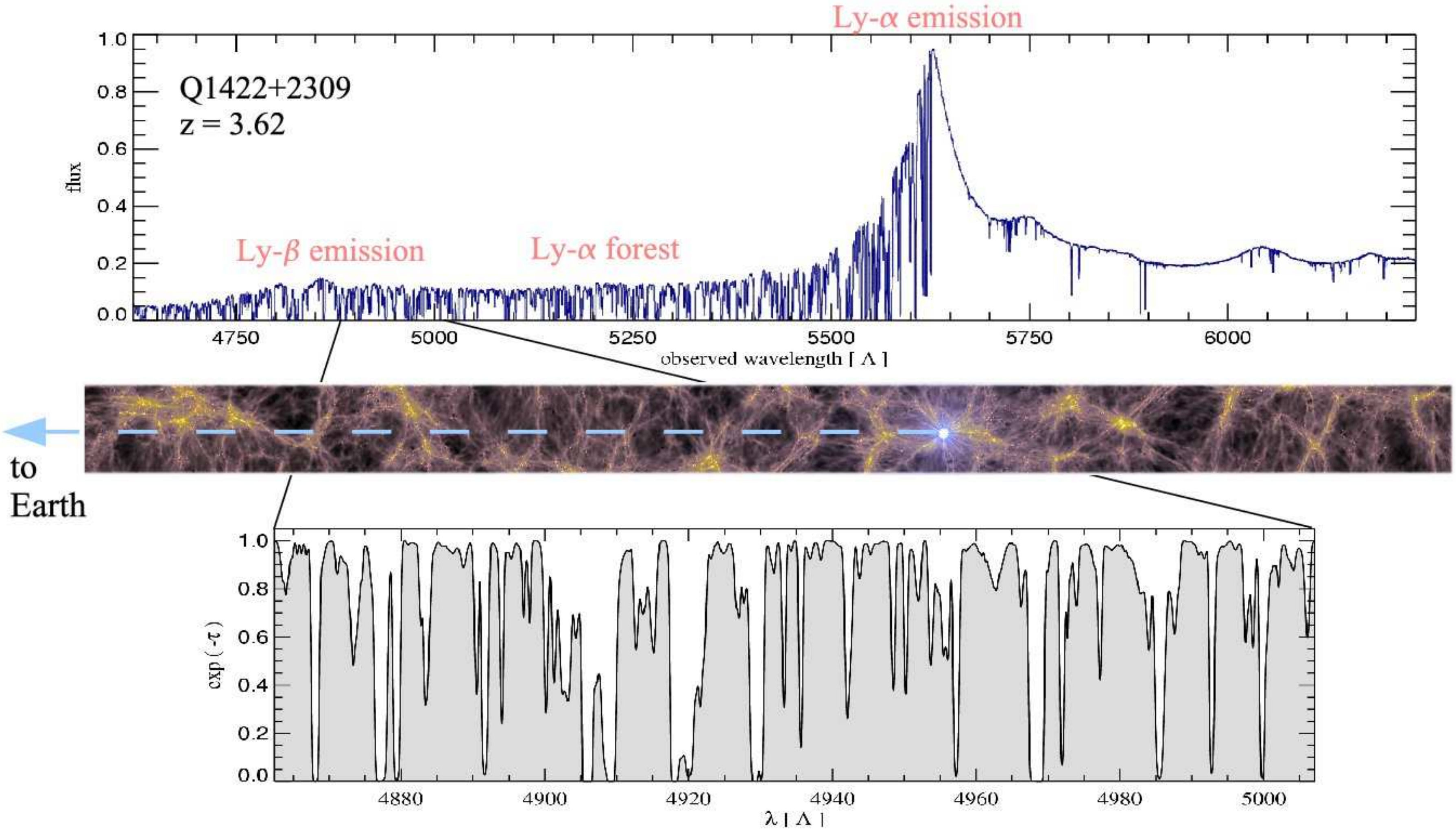
[WMAP, http://map.gsfc.nasa.gov]

Galaxy Redshift Surveys



[Springel, Frenk, White, astro-ph/0604561]

Lyman-alpha Forest



[Springel, Frenk, White, astro-ph/0604561]

Rest-frame Lyman α, β, γ wavelengths: $\lambda^0_\alpha = 1215.67\,\AA$, $\lambda^0_\beta = 1025.72\,\AA$, $\lambda^0_\gamma = 972.54\,\AA$

Lyman-α forest: The region in which only Lyα photons can be absorbed: $[(1+z_q)\lambda^0_\beta, (1+z_q)\lambda^0_\alpha]$

Lyman-α+β region: $[(1+z_q)\lambda^0_\gamma, (1+z_q)\lambda^0_\beta]$

Relic Neutrinos

neutrinos are in equilibrium in primeval plasma through weak interaction reactions

$$\nu\bar{\nu} \leftrightarrows e^+ e^- \quad \overset{(-)}{\nu} e \leftrightarrows \overset{(-)}{\nu} e \quad \overset{(-)}{\nu} N \leftrightarrows \overset{(-)}{\nu} N \quad \nu_e n \leftrightarrows p e^- \quad \bar{\nu}_e p \leftrightarrows n e^+ \quad n \leftrightarrows p e^- \bar{\nu}_e$$

weak interactions freeze out

$$\Gamma_{\text{weak}} = N \sigma v \sim G_F^2 T^5 \sim T^2 / M_P \sim \sqrt{G_N T^4} \sim \sqrt{G_N \rho} \sim H \Longrightarrow \underset{\text{neutrino decoupling}}{T_{\text{dec}} \sim 1\,\text{MeV}}$$

Relic Neutrinos: $T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma \simeq 1.945\,\text{K} \Longrightarrow k\, T_\nu \underset{(T_\gamma = 2.725 \pm 0.001\,\text{K})}{\simeq} 1.676 \times 10^{-4}\,\text{eV}$

number density: $n_f = \frac{3}{4} \frac{\zeta(3)}{\pi^2} g_f T_f^3 \Longrightarrow n_{\nu_k, \bar{\nu}_k} \simeq 0.1827\, T_\nu^3 \simeq 112\,\text{cm}^{-3}$

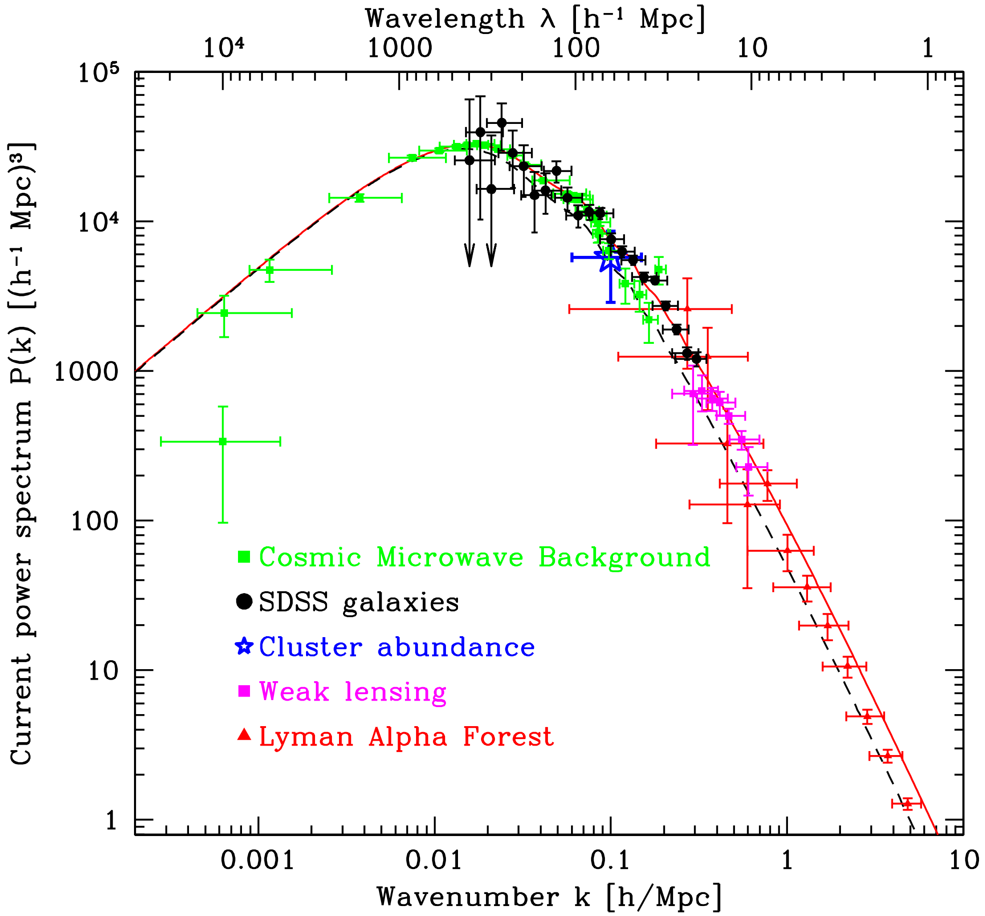
density contribution: $\Omega_k = \frac{n_{\nu_k, \bar{\nu}_k} m_k}{\rho_c} \simeq \frac{1}{h^2} \frac{m_k}{94.14\,\text{eV}} \Longrightarrow \boxed{\Omega_\nu h^2 = \frac{\sum_k m_k}{94.14\,\text{eV}}}$

$\left(\rho_c = \frac{3H^2}{8\pi G_N}\right)$

[Gershtein, Zeldovich, JETP Lett. 4 (1966) 120] [Cowsik, McClelland, PRL 29 (1972) 669]

$$h \sim 0.7, \quad \Omega_\nu \lesssim 0.3 \quad \Longrightarrow \quad \sum_k m_k \lesssim 14\,\text{eV}$$

Power Spectrum of Density Fluctuations



[Tegmark, hep-ph/0503257]

Solid Curve: flat scalar scale-invariant ΛCDM model

$(\Omega_{\mathrm{M}}^{0} = 0.28\,,\ h = 0.72\,,\ \Omega_{\mathrm{B}}^{0}/\Omega_{\mathrm{M}}^{0} = 0.16)$

Dashed Curve: $\sum_{k=1}^{3} m_k = 1\,\mathrm{eV}$

hot dark matter
prevents early galaxy formation

small scale suppression

$$\frac{\Delta P(k)}{P(k)} \approx -8\,\frac{\Omega_\nu}{\Omega_m} \approx -0.8 \left(\frac{\sum_k m_k}{1\,\mathrm{eV}}\right)\left(\frac{0.1}{\Omega_m h^2}\right)$$

for

$$k \gtrsim k_{\mathrm{nr}} \approx 0.026 \sqrt{\frac{m_\nu}{1\,\mathrm{eV}}}\sqrt{\Omega_m}\, h\,\mathrm{Mpc}^{-1}$$

[Hu, Eisenstein, Tegmark, PRL 80 (1998) 5255]

WMAP, AJ SS 148 (2003) 175, astro-ph/0302209

CMB (WMAP, ...) + LSS (2dFGRS) + HST + SNIa $\Longrightarrow$ ΛCDM

$$T_0 = 13.7 \pm 0.1\,\text{Gyr} \qquad h = 0.71^{+0.04}_{-0.03}$$

$$\Omega_0 = 1.02 \pm 0.02 \qquad \Omega_B h^2 = 0.0224 \pm 0.0009 \qquad \Omega_M h^2 = 0.135^{+0.008}_{-0.009}$$

$$\Omega_\nu h^2 < 0.0076 \quad (95\%\ \text{conf.}) \quad \Longrightarrow \quad \boxed{\sum_{k=1}^{3} m_k < 0.71\,\text{eV}}$$

WMAP, astro-ph/0603449

Flat ΛCDM (WMAP+HST: $\Omega_0 = 1.010^{+0.016}_{-0.009}$, $\Omega_\Lambda = 0.72 \pm 0.04$)

$$\sum_{k=1}^{3} m_k < \begin{cases} 2.0\,\text{eV} & \text{WMAP} \\ 0.91\,\text{eV} & \text{WMAP+SDSS} \\ 0.87\,\text{eV} & \text{WMAP+2dFGRS} \\ 0.68\,\text{eV} & \text{CMB+LSS+SNIa} \end{cases} \quad (95\%\ \text{conf.})$$

$$N_\nu = 3.29^{+0.45}_{-2.18} \quad \text{CMB+LSS+SNIa}$$

Goobar, Hannestad, Mortsell, Tu, astro-ph/0602155

Flat ΛCDM

$$\sum_{k=1}^{3} m_k < \begin{cases} 2.3\,\text{eV} & \text{CMB+LSS+SNIa} \\ 0.48\,\text{eV} & \text{CMB+LSS+SNIa+BAO} \\ 0.30\,\text{eV} & \text{CMB+LSS+SNIa+BAO+Ly}\alpha \end{cases} \qquad (95\%\ \text{conf.})$$

Seljak, Slosar, McDonald, astro-ph/0604335

Flat ΛCDM CMB+LSS+SNIa+Lyα

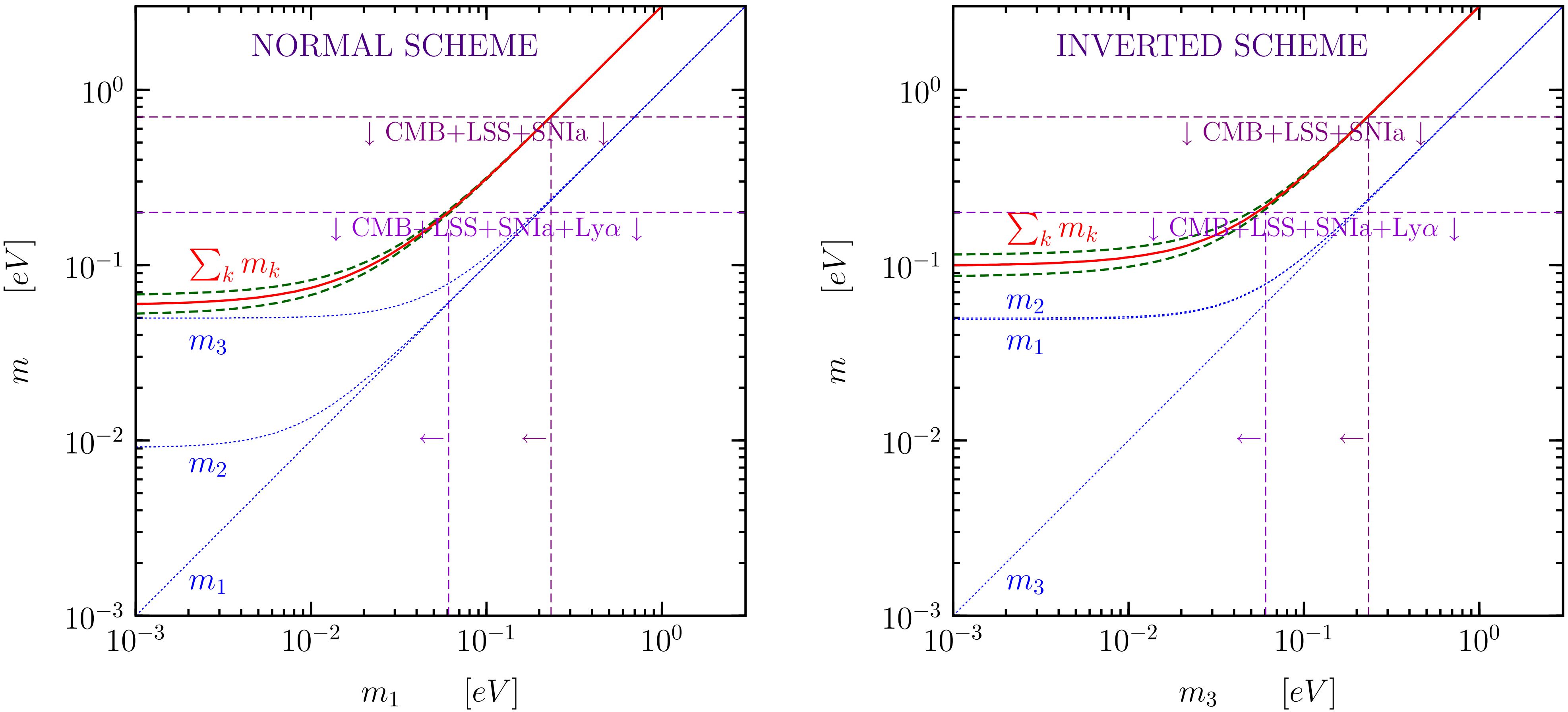
$$\sum_{k=1}^{3} m_k < 0.17\,\text{eV} \qquad (95\%\ \text{conf.})$$

$$m_4 < 0.14\,\text{eV} \qquad (95\%\ \text{conf.})$$

$$N_\nu = 3.19^{+0.19}_{-0.15}$$

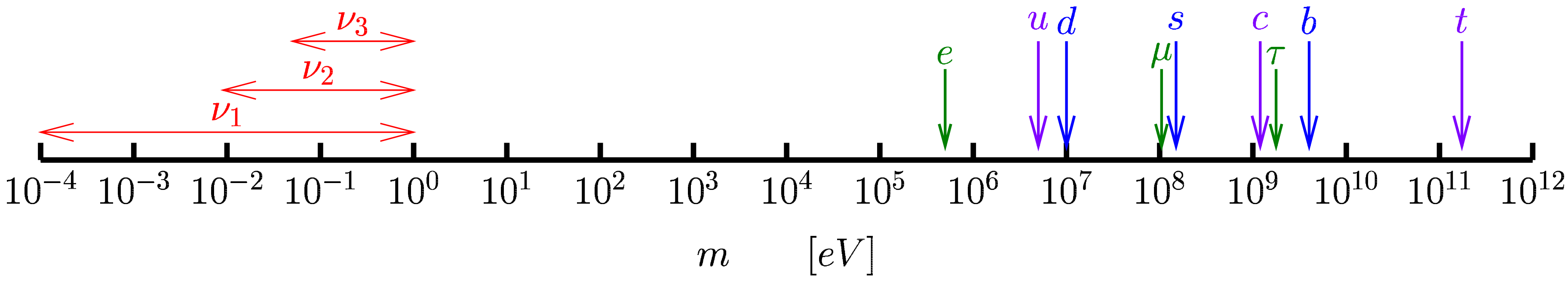
$$\sum_{k=1}^{3} m_k \lesssim 0.7\,\text{eV} \qquad (\sim 2\sigma) \qquad \text{CMB+LSS+SNIa}$$

$$\sum_{k=1}^{3} m_k \lesssim 0.2\,\text{eV} \qquad (\sim 2\sigma) \qquad \text{CMB+LSS+SNIa+Ly}\alpha$$



FUTURE: IF $\sum_{k=1}^{3} m_k \lesssim 8 \times 10^{-2}\,\text{eV} \Longrightarrow$ NORMAL HIERARCHY

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

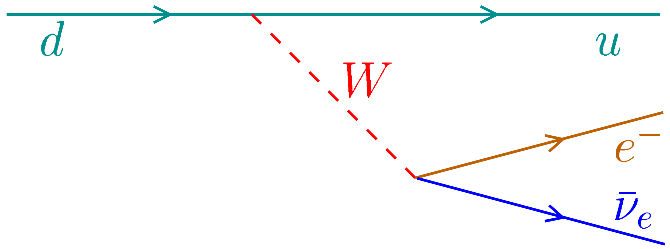
Majorana neutrino masses provide the most accessible window on New Physics Beyond the Standard Model

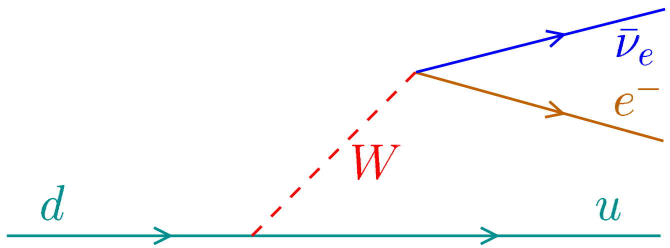
Two-Neutrino Double-β Decay: $\Delta L = 0$

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

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

second order weak interaction process in the Standard Model



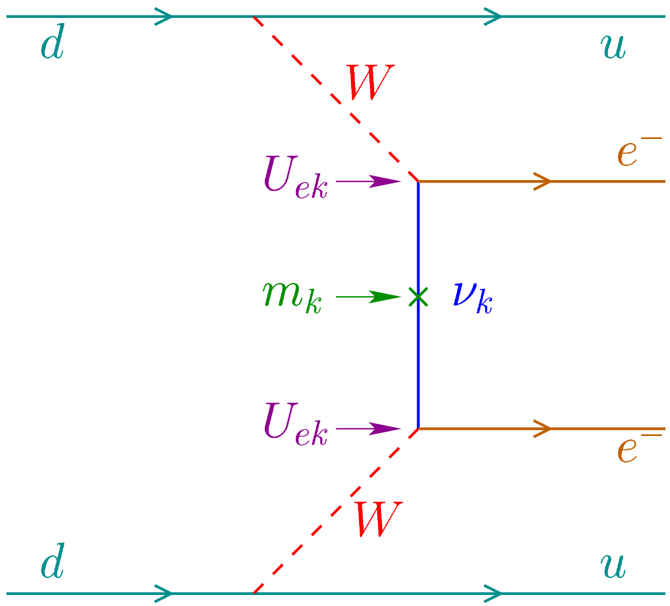


Neutrinoless Double-β Decay: $\Delta L = 2$

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

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

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

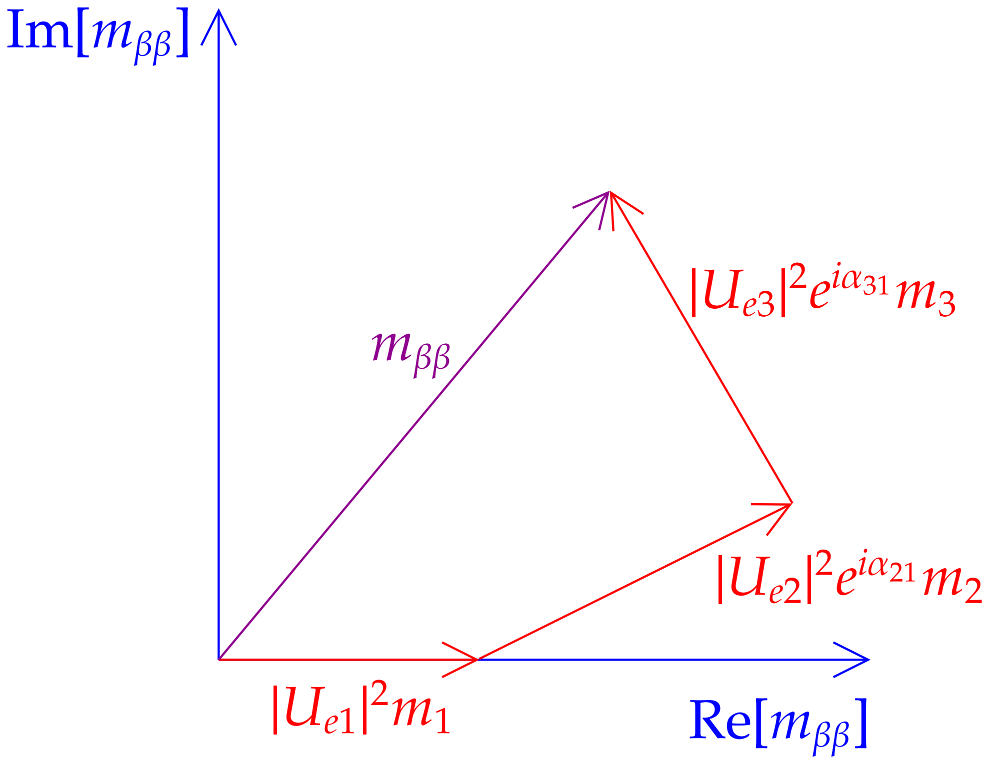


Effective Majorana Neutrino Mass

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

complex U_{ek} $\Rightarrow$ possible cancellations

$$m_{\beta\beta} = |U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, e^{i\alpha_{21}} \, m_2 + |U_{e3}|^2 \, e^{i\alpha_{31}} \, m_3$$



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

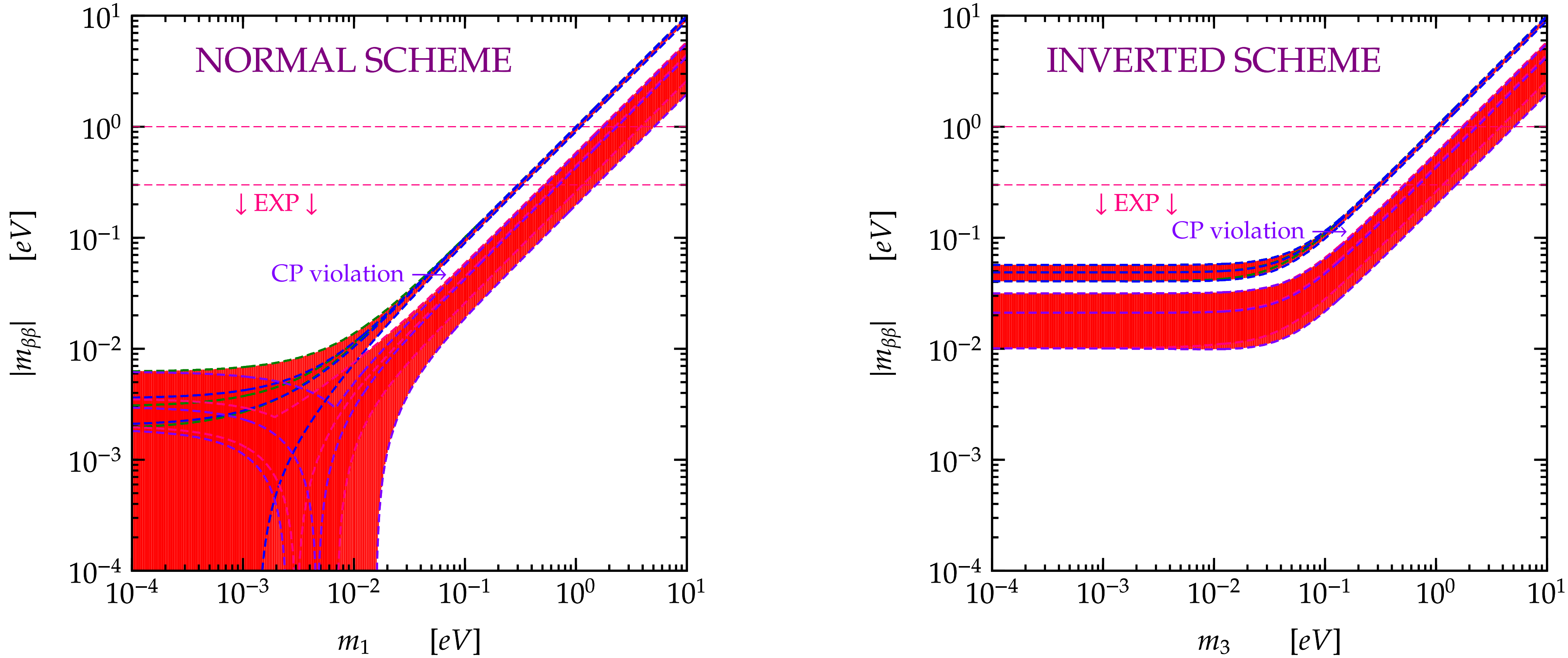
$$|m_{\beta\beta}| \sim \text{few}\,10^{-1}\,\text{eV}$$

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

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

Bounds from Neutrino Oscillations

$$m_{\beta\beta} = |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_{21}}\, m_2 + |U_{e3}|^2\, e^{i\alpha_{31}}\, m_3$$

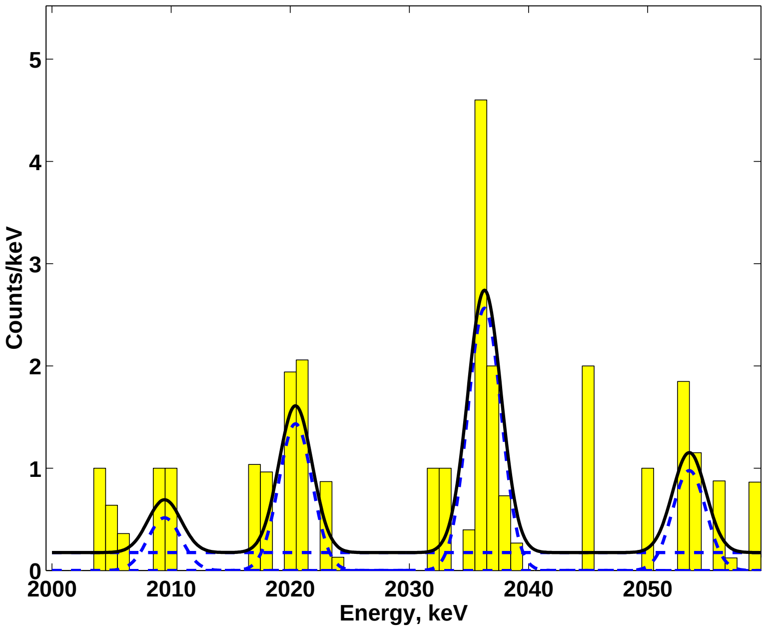


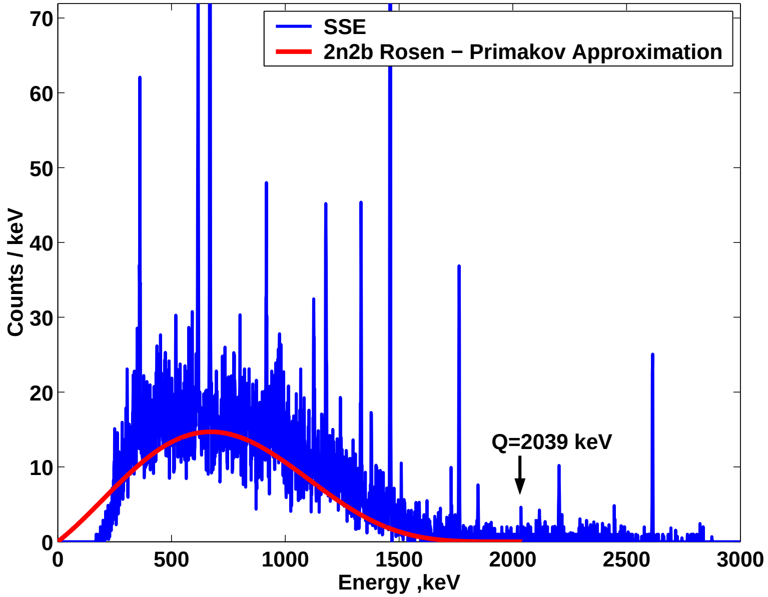
FUTURE: IF $|m_{\beta\beta}| \lesssim 10^{-2}\,\mathrm{eV} \Longrightarrow$ NORMAL HIERARCHY

Experimental Positive Indication

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

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





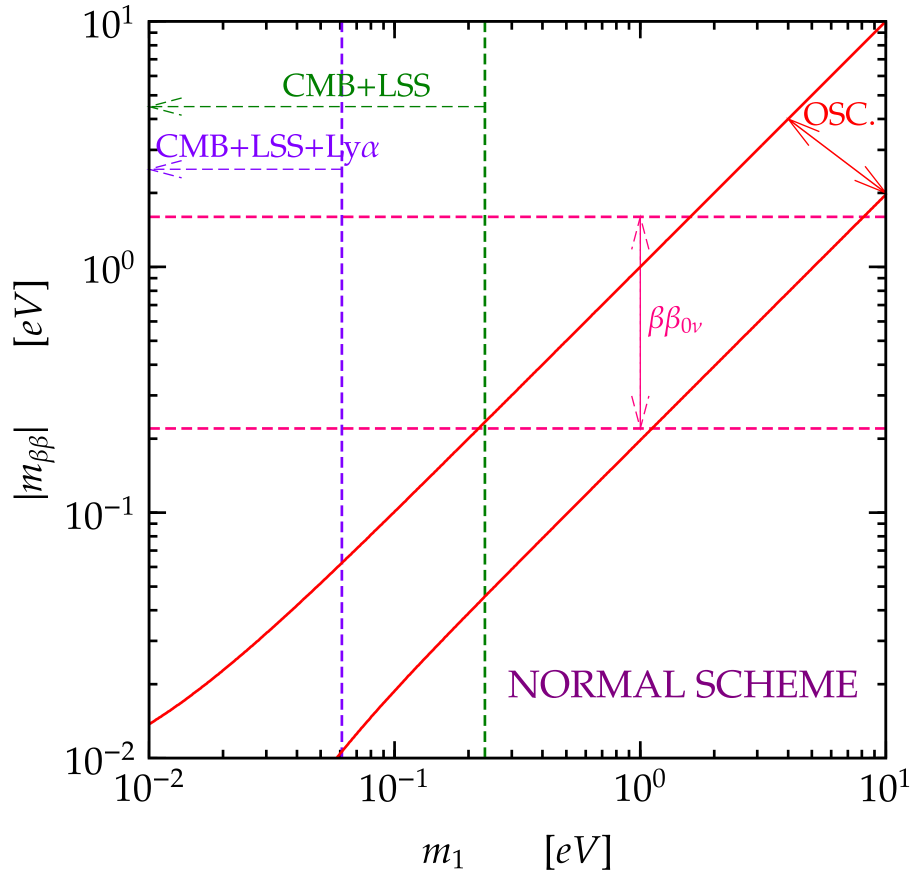
pulse-shape selected spectrum $\quad 3.8\sigma$ evidence $\quad$ [PLB 586 (2004) 198]

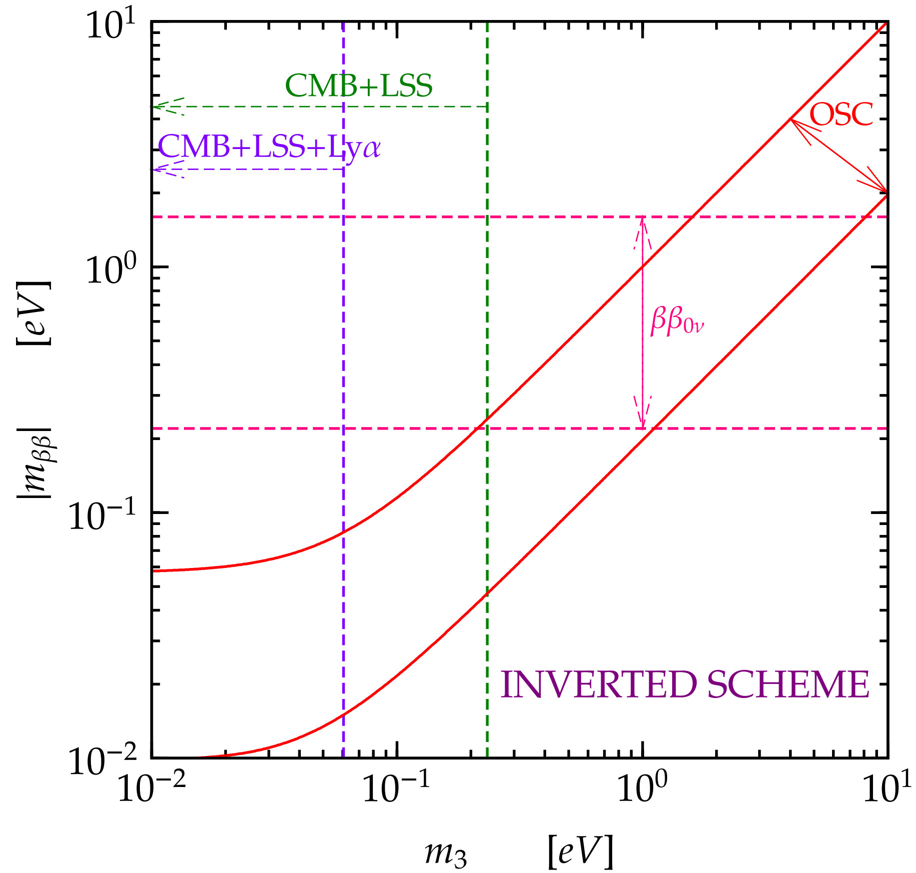
the indication must be checked by other experiments

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

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

Indication of $\beta\beta_{0\nu}$ Decay: $0.22\,\text{eV} \lesssim |m_{\beta\beta}| \lesssim 1.6\,\text{eV}$ $(\sim 3\sigma$ range$)$

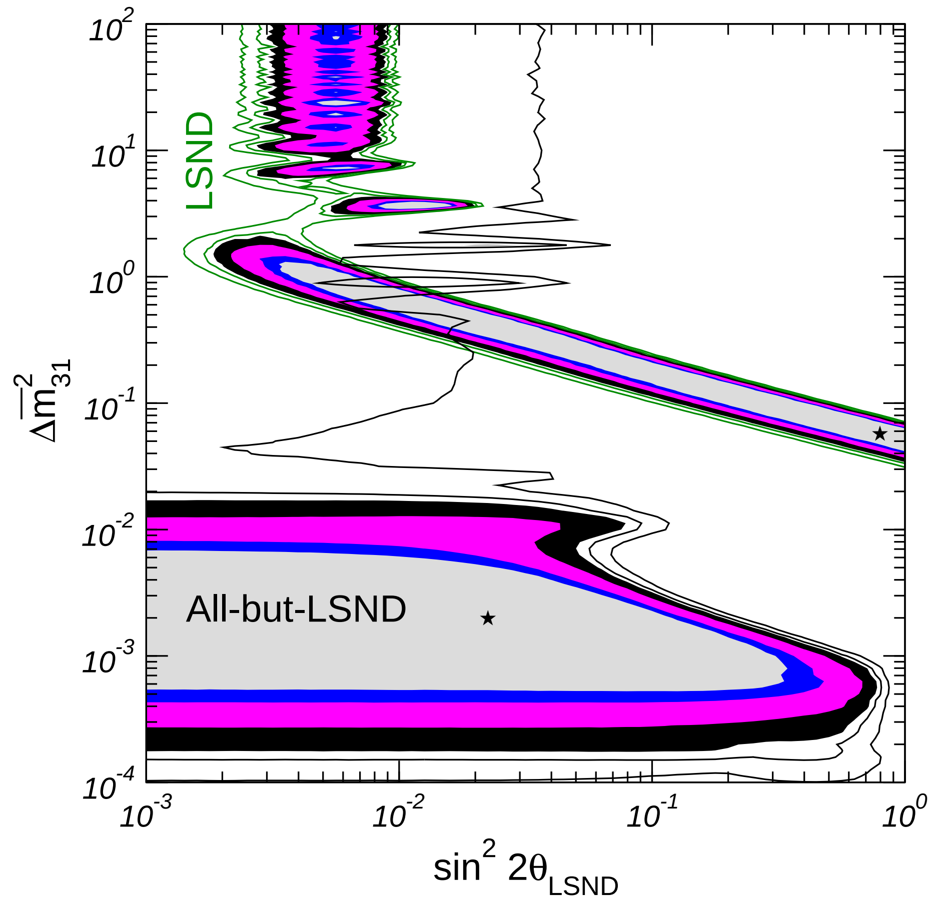




tension among oscillation data, CMB+LSS+Lyα and $\beta\beta_{0\nu}$ signal

LSND

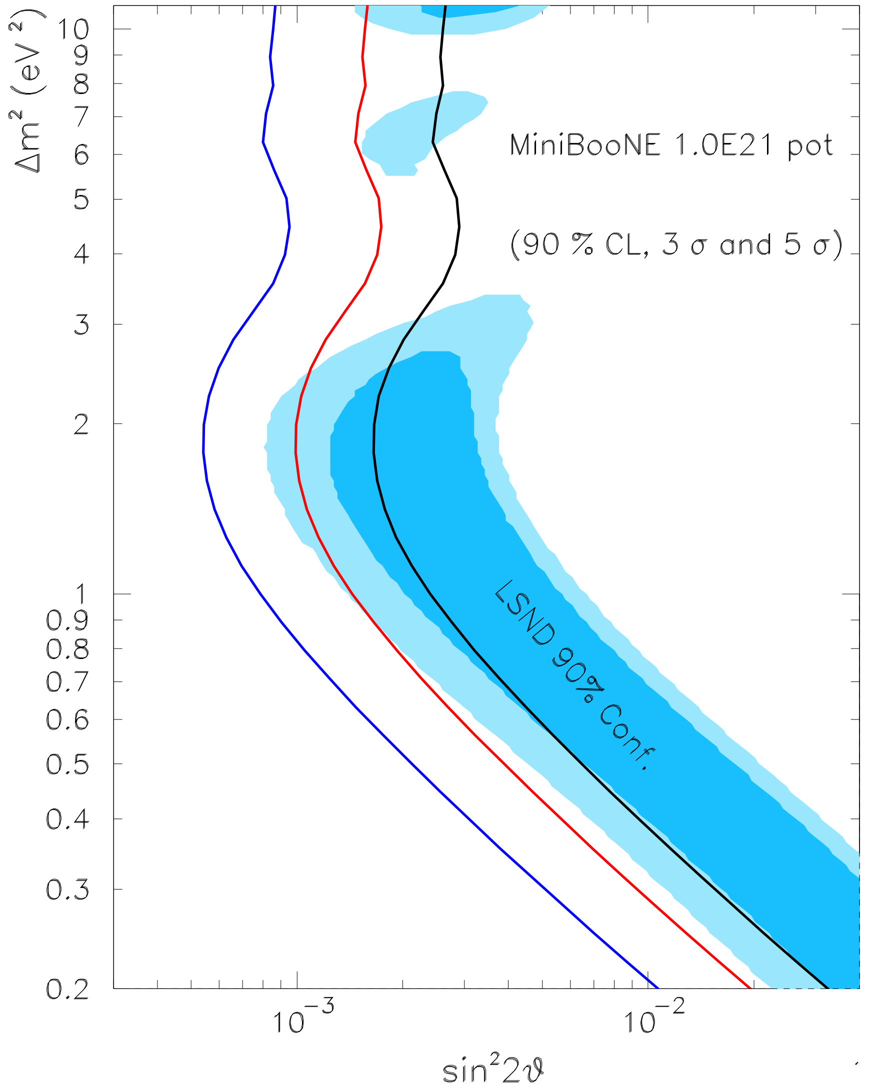
$\bar{\nu}_\mu \to \bar{\nu}_e$ $\Delta m^2_{\text{LSND}} \gtrsim 0.1\,\text{eV}^2$ $(\gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SUN}})$



[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 $\Delta m^2_{\text{ATM}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2$ (atmospheric ν, K2K)

$\Downarrow$

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

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