

Status of Neutrino Masses and Mixing

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Introduction to Neutrino Masses, Mixing and Oscillations

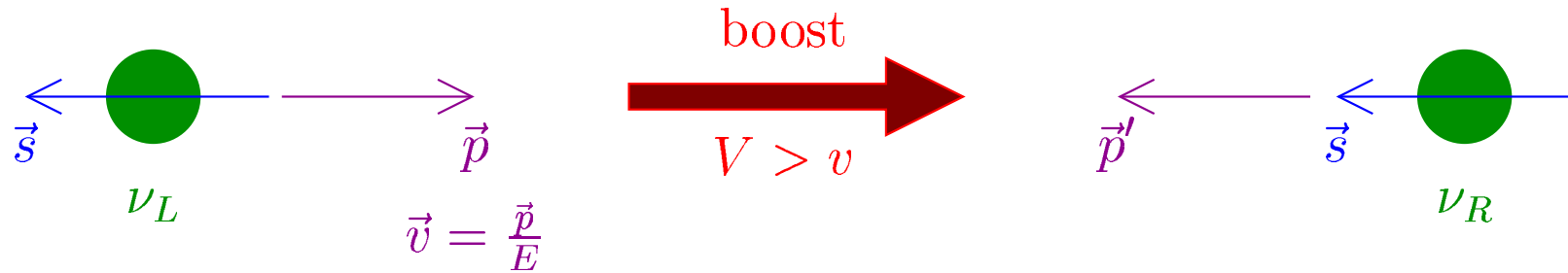
Solar $\nu_e \rightarrow \nu_\mu, \nu_\tau$ + Atmospheric $\nu_\mu \rightarrow \nu_\tau \implies$ 3- ν Mixing

Absolute Scale of Neutrino Masses

Cosmological Bound on Neutrino Masses

Neutrinoless Double- β Decay \iff Majorana Mass

Neutrino Mass



Standard Model: $\nu_L, \bar{\nu}_R \implies$ no Dirac mass term $\sim \nu_L \nu_R$ (no $\nu_R, \bar{\nu}_L$)

Majorana Neutrino: $\nu = \bar{\nu}$

$\bar{\nu}_R = \nu_R \implies$ Majorana mass term $\sim \nu_L \bar{\nu}_R$

Standard Model: Majorana mass term **not** allowed by $SU(2)_L \times U(1)_Y$
(no Higgs triplet)

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

$\nu_L + \nu_R \implies$ Dirac neutrino mass term $\sim \nu_L \nu_R \implies m^D \lesssim 100 \text{ GeV}$

surprise: also Majorana neutrino mass for ν_R is allowed!

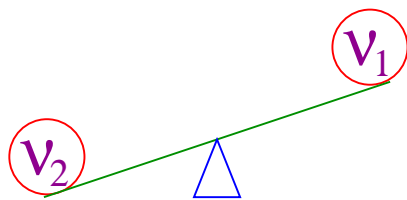
Lagrangian neutrino mass term $\sim (\nu_L \quad \bar{\nu}_L) \begin{pmatrix} 0 & m^D \\ m^D & m_R^M \end{pmatrix} \begin{pmatrix} \bar{\nu}_R \\ \nu_R \end{pmatrix}$

m_R^M can be arbitrarily large (not protected by SM symmetries)

$m_R^M \sim$ scale of new physics beyond Standard Model $\implies m_R^M \gg m^D$

diagonalization of $\begin{pmatrix} 0 & m^D \\ m^D & m_R^M \end{pmatrix} \implies m_1 \simeq \frac{(m^D)^2}{m_R^M}, \quad m_2 \simeq m_R^M$

natural explanation of
smallness of neutrino masses



see-saw mechanism

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		L_e	L_μ	L_τ
(ν_e, e^-)	+1	0	0	$(\bar{\nu}_e, e^+)$	-1	0	0
(ν_μ, μ^-)	0	+1	0	$(\bar{\nu}_\mu, \mu^+)$	0	-1	0
(ν_τ, τ^-)	0	0	+1	$(\bar{\nu}_\tau, \tau^+)$	0	0	-1

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

Dirac mass term $\sim \nu_L \nu_R \implies (\nu_{eL} \ \nu_{\mu L} \ \nu_{\tau L}) \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{\mu e} & m_{\mu\mu} & m_{\mu\tau} \\ m_{\tau e} & m_{\tau\mu} & m_{\tau\tau} \end{pmatrix} \begin{pmatrix} \nu_{eR} \\ \nu_{\mu R} \\ \nu_{\tau R} \end{pmatrix}$

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

Majorana mass term $\sim \nu_L \bar{\nu}_R \implies (\nu_{eL} \ \nu_{\mu L} \ \nu_{\tau L}) \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{\mu e} & m_{\mu\mu} & m_{\mu\tau} \\ m_{\tau e} & m_{\tau\mu} & m_{\tau\tau} \end{pmatrix} \begin{pmatrix} \bar{\nu}_{eR} \\ \bar{\nu}_{\mu R} \\ \bar{\nu}_{\tau R} \end{pmatrix}$

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

Neutrino Oscillations

[Pontecorvo, SPJETP 6 (1957) 429] [Pontecorvo, SPJETP 7 (1958) 172] [Gribov, Pontecorvo, PLB 28 (1969) 49]

[Eliezer, Swift, NPB 105 (1976) 45] [Fritzsch, Minkowski, PLB 62 (1976) 72] [Bilenky, Pontecorvo, SJNP 24 (1976) 316]

[Bilenky, Pontecorvo, NCimL 17 (1976) 56] [Bilenky, Pontecorvo, PRep 41 (1978) 225]

Neutrino Mixing:

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle$$

$$\alpha = e, \mu, \tau$$

$$\nu_k \rightarrow m_k$$

$$|\nu_k(x, t)\rangle = e^{-iE_k t + ip_k x} |\nu_k\rangle \implies |\nu_\alpha(x, t)\rangle = \sum_k U_{\alpha k} e^{-iE_k t + ip_k x} |\nu_k\rangle$$

$$|\nu_k\rangle = \sum_{\beta=e,\mu,\tau} U_{\beta k}^* |\nu_\beta\rangle$$

$$|\nu_\alpha(x, t)\rangle = \sum_{\beta=e,\mu,\tau} \underbrace{\left(\sum_k U_{\alpha k} e^{-iE_k t + ip_k x} U_{\beta k}^* \right)}_{A_{\nu_\alpha \rightarrow \nu_\beta}(x, t)} |\nu_\beta\rangle$$

Transition Probability

$$P_{\nu_\alpha \rightarrow \nu_\beta}(x, t) = |\langle \nu_\beta | \nu_\alpha(x, t) \rangle|^2 = |\mathcal{A}_{\nu_\alpha \rightarrow \nu_\beta}(x, t)|^2 = \left| \sum_k U_{\alpha k} e^{-iE_k t + ip_k x} U_{\beta k}^* \right|^2$$

ultrarelativistic neutrinos $\implies t \simeq x = L$ source-detector distance

$$E_k t - p_k x \simeq (E_k - p_k) L = \frac{E_k^2 - p_k^2}{E_k + p_k} L = \frac{m_k^2}{E_k + p_k} L \simeq \frac{m_k^2}{2E} L$$

$$\begin{aligned} P_{\nu_\alpha \rightarrow \nu_\beta}(L, E) &= \left| \sum_k U_{\alpha k} e^{-im_k^2 L/2E} U_{\beta k}^* \right|^2 \\ &= \sum_{k,j} U_{\alpha k} U_{\beta k}^* U_{\alpha j}^* U_{\beta j} \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right) \end{aligned}$$

Two-Neutrino Mixing

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

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

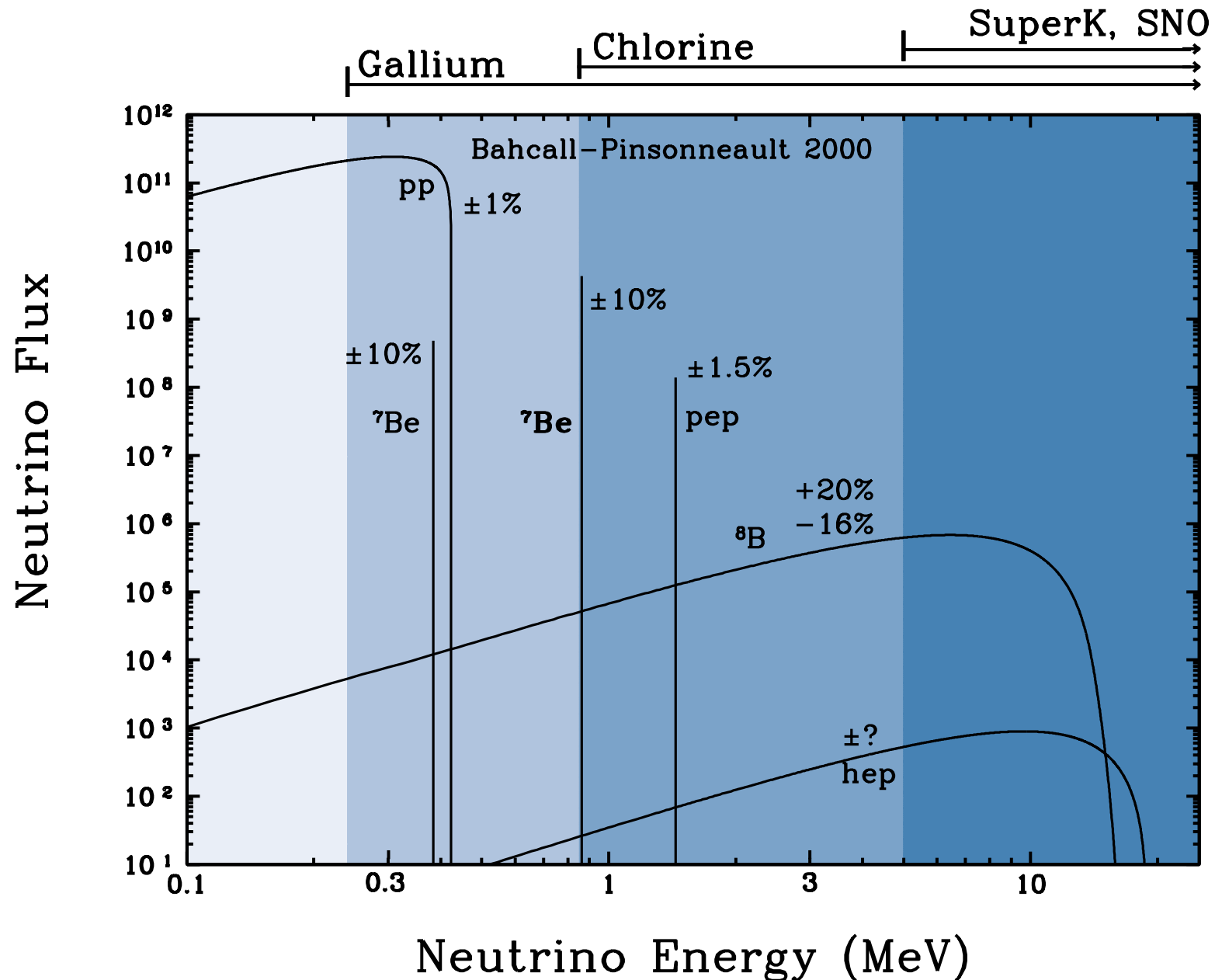
$$\begin{aligned} |\nu_e\rangle &= \cos \vartheta |\nu_1\rangle + \sin \vartheta |\nu_2\rangle \\ |\nu_\mu\rangle &= -\sin \vartheta |\nu_1\rangle + \cos \vartheta |\nu_2\rangle \end{aligned}$$

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

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

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

Solar Neutrinos



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

SNO

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

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

SNO solved
solar neutrino problem



Neutrino Physics
(April 2002)

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

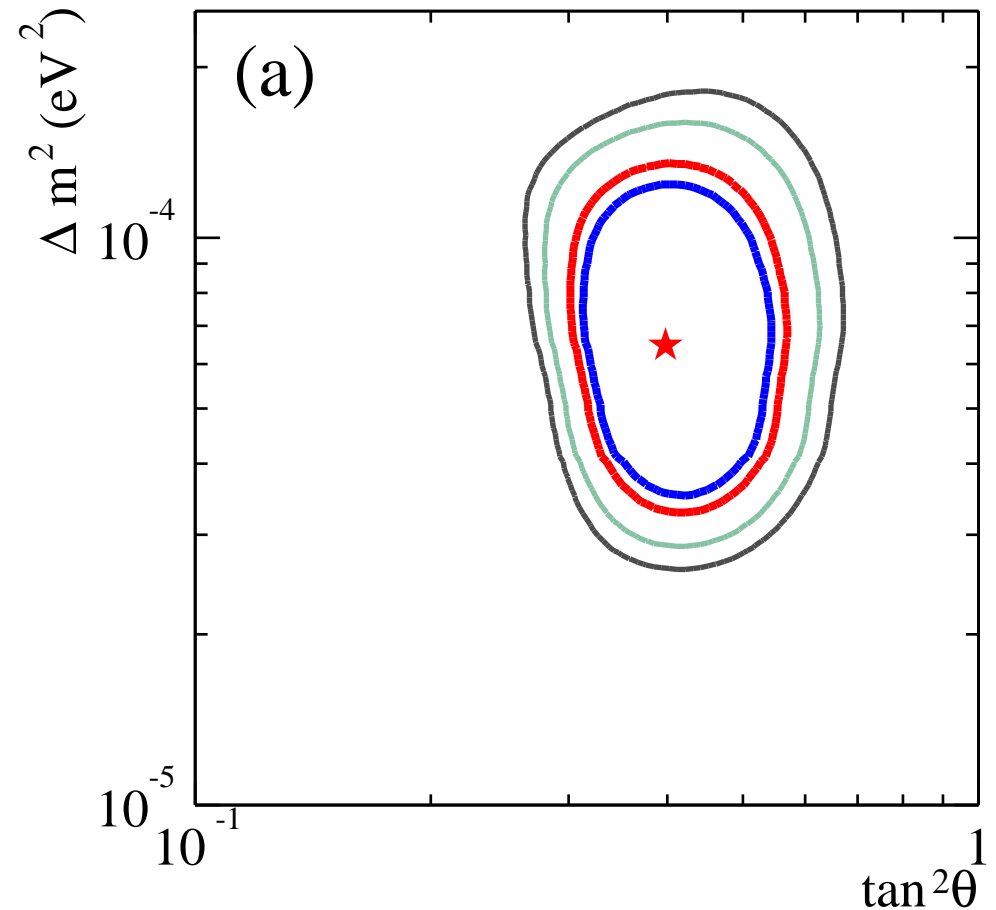
$\nu_e \rightarrow \nu_{\mu}, \nu_{\tau}$ oscillations



Large Mixing Angle solution

$$\Delta m^2 \simeq 5 \times 10^{-5} \text{ eV}^2$$

$$\tan^2 \vartheta \simeq 0.4$$

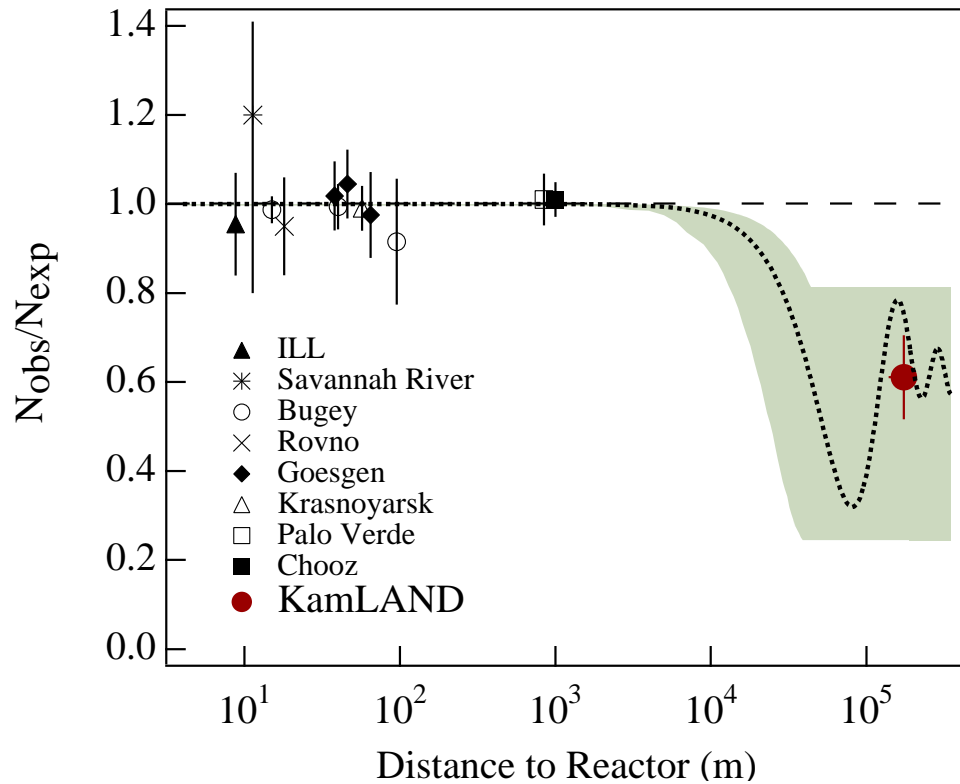


90%, 95%, 99%, 99.73% C.L.

[SNO, PRL 92 (2004) 181301, nucl-ex/0309004]

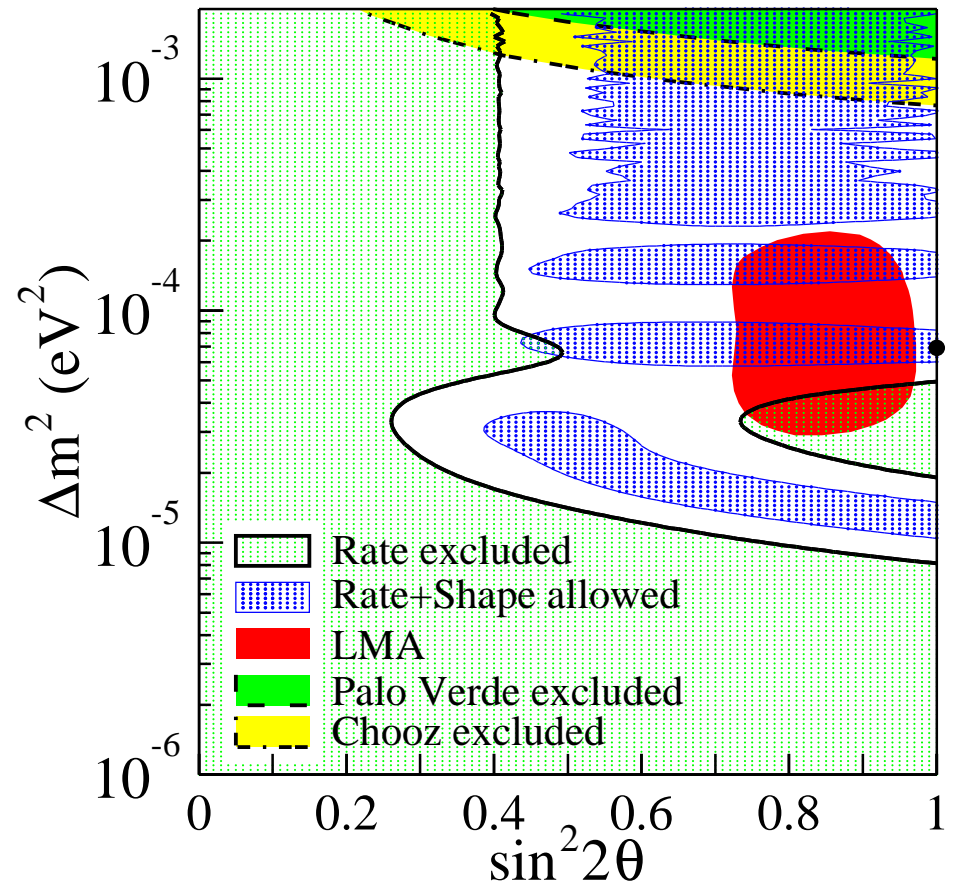
KamLAND

confirmation of LMA (December 2002)



Shade: 95% C.L. LMA

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

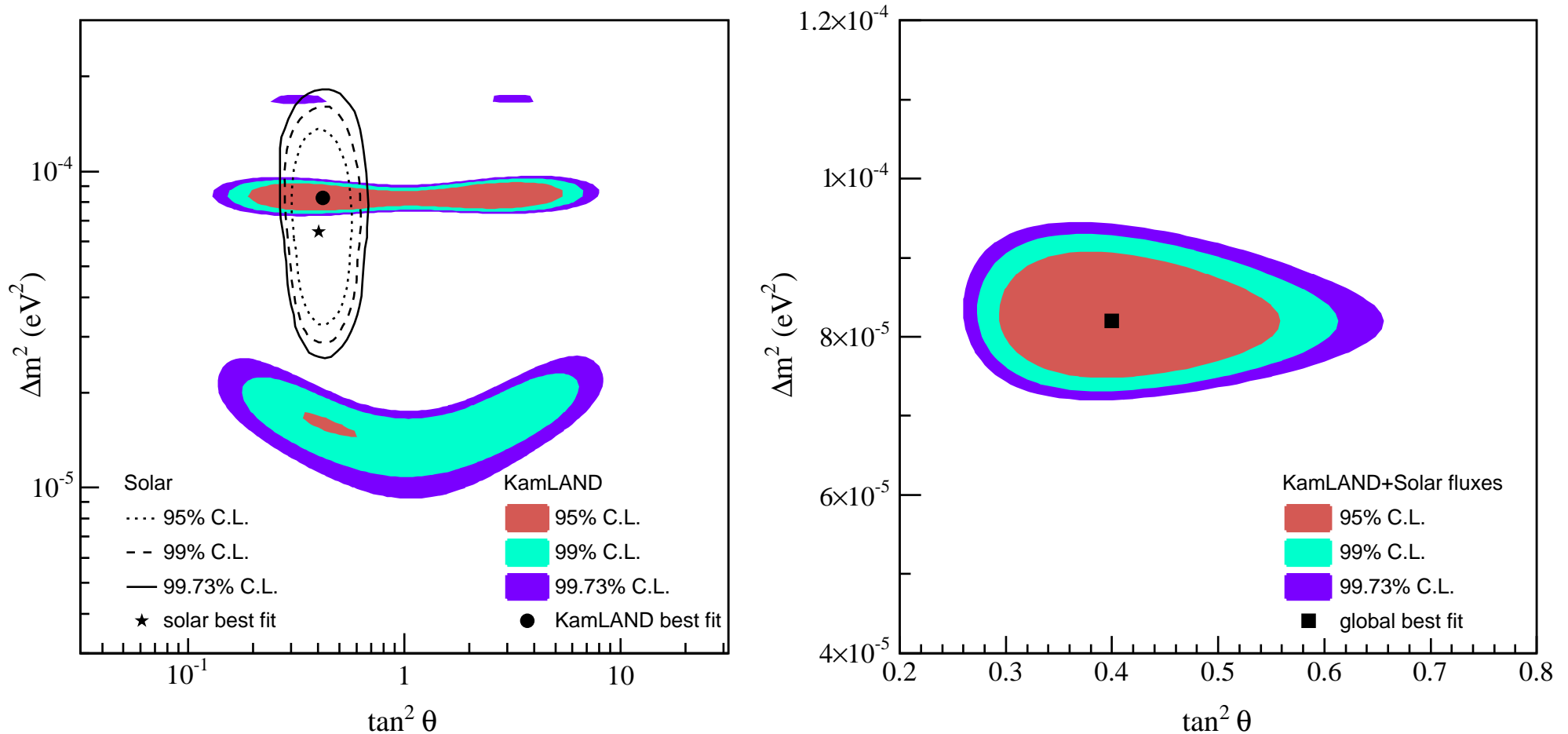


95% C.L.

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

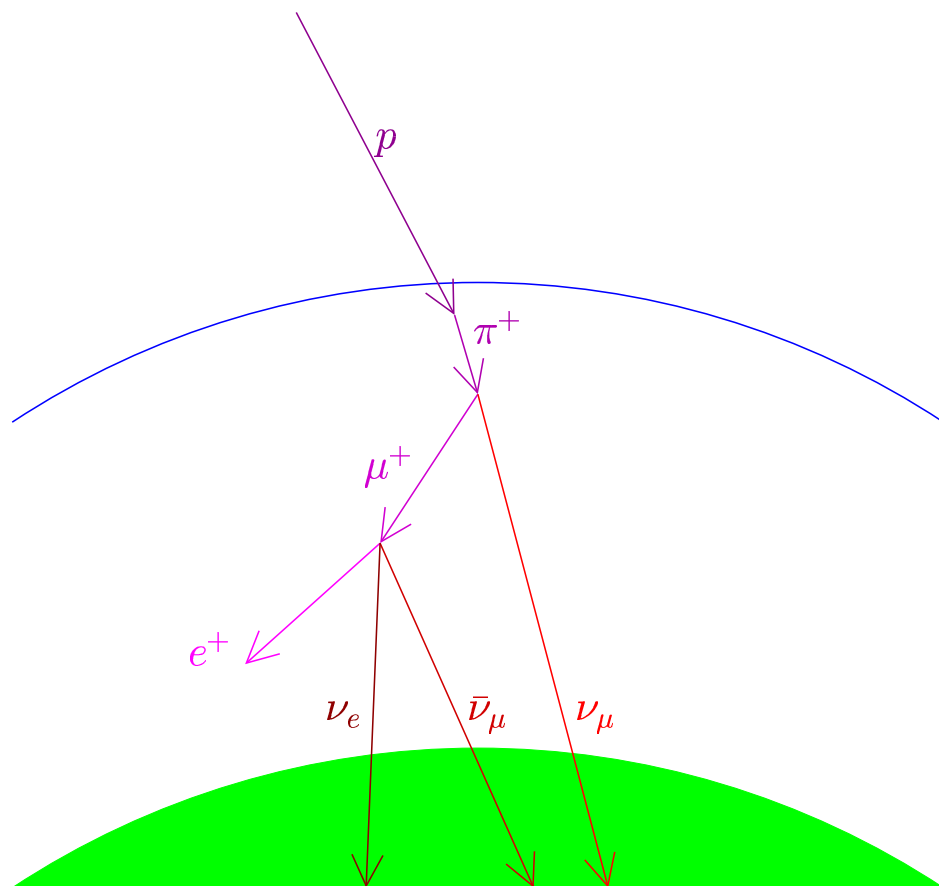
Combined Fit of Solar + Reactor Neutrino Data

[KamLAND, hep-ex/0406035]



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

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

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

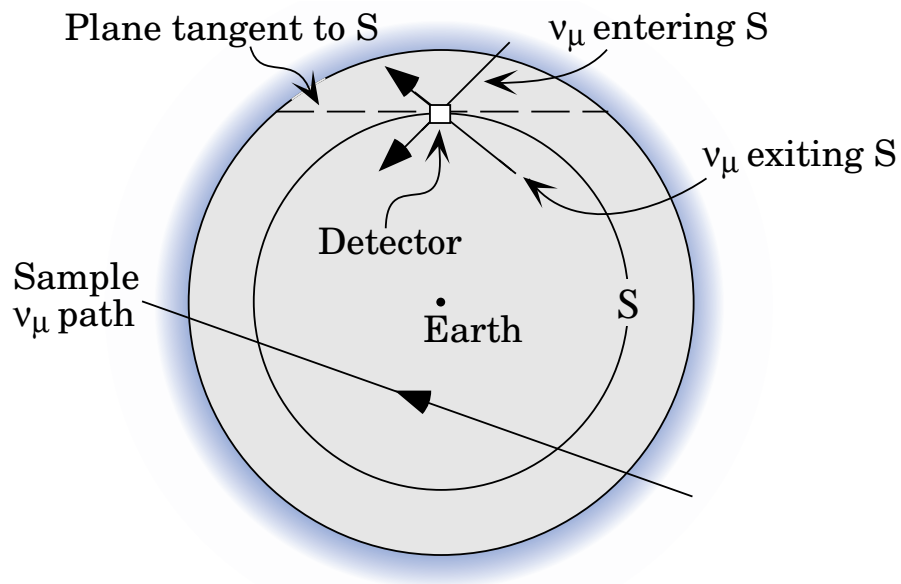
$$R_{\text{sub-GeV}}^{\text{K}} = 0.60 \pm 0.07 \pm 0.05$$

[Kamiokande, PLB 280 (1992) 146]

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

[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 $\Rightarrow \Phi^{\text{in}}(s) = \Phi^{\text{out}}(s), \forall s \in S$
- $D \in S \Rightarrow \Phi^{\text{up}}(D) = \Phi^{\text{down}}(D),$

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

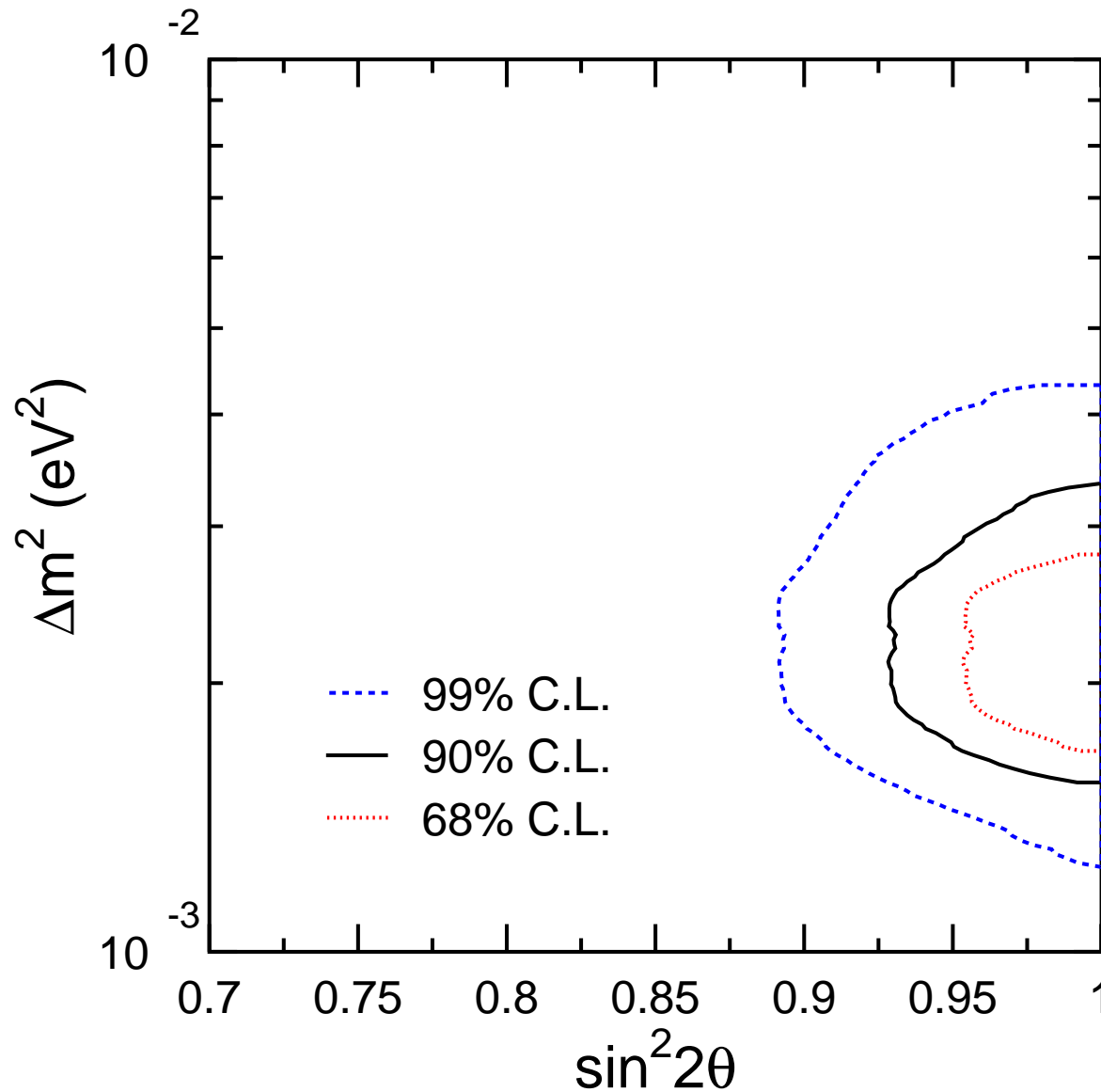
(December 1998)

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

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

6σ MODEL INDEPENDENT EVIDENCE OF ν_μ DISAPPEARANCE!

$\nu_\mu \rightarrow \nu_\tau$ Fit of Super-Kamiokande Atmospheric Data

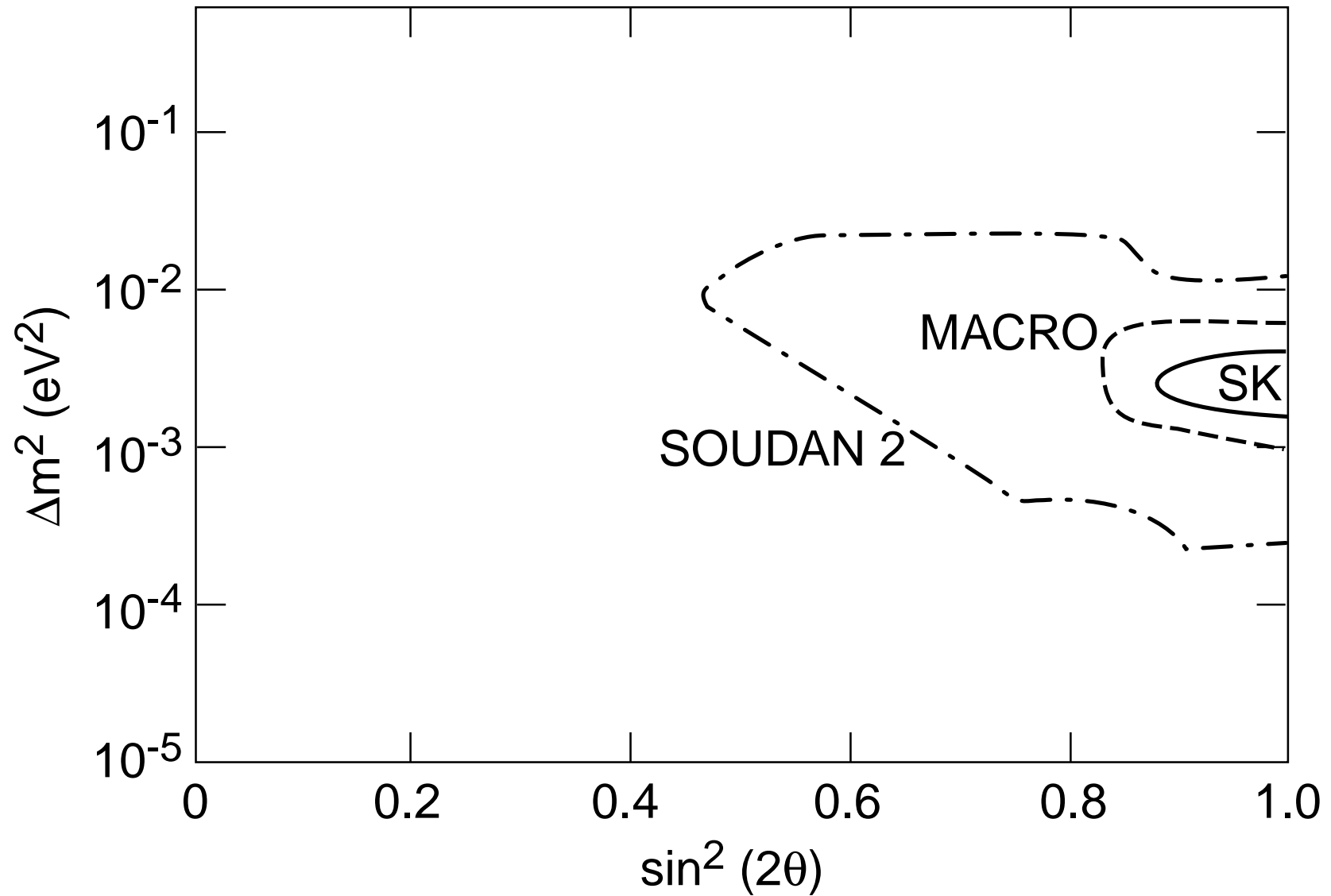


Best Fit
 $\Delta m^2 = 2.1 \times 10^{-3} \text{ eV}^2$
 $\sin^2 2\theta = 1.0$

1489 live-days
April 1996 – July 2001

[Super-Kamiokande, hep-ex/0501064]

Soudan-2 & MACRO



[Giacomelli, Giorgini, Spurio, hep-ex/0201032]

Three-Neutrino Mixing

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

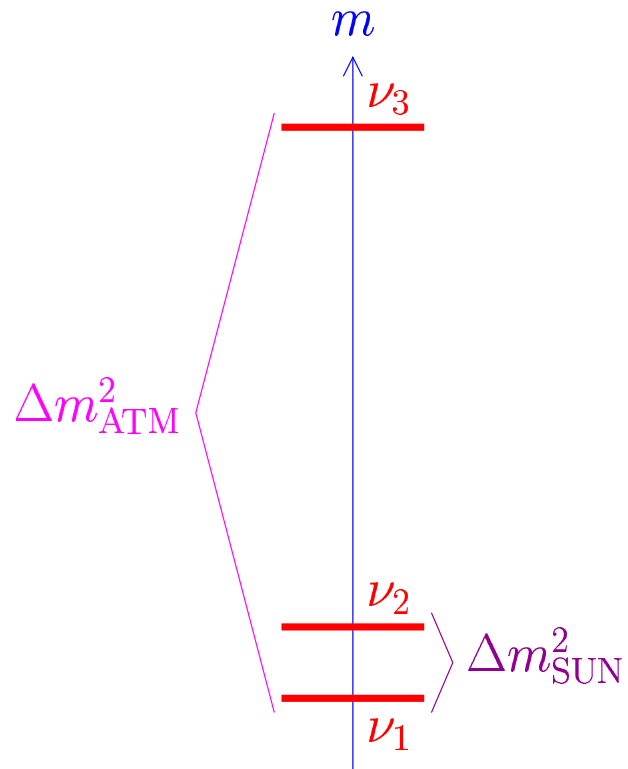
three flavor fields ν_e, ν_μ, ν_τ

three massive fields ν_1, ν_2, ν_3

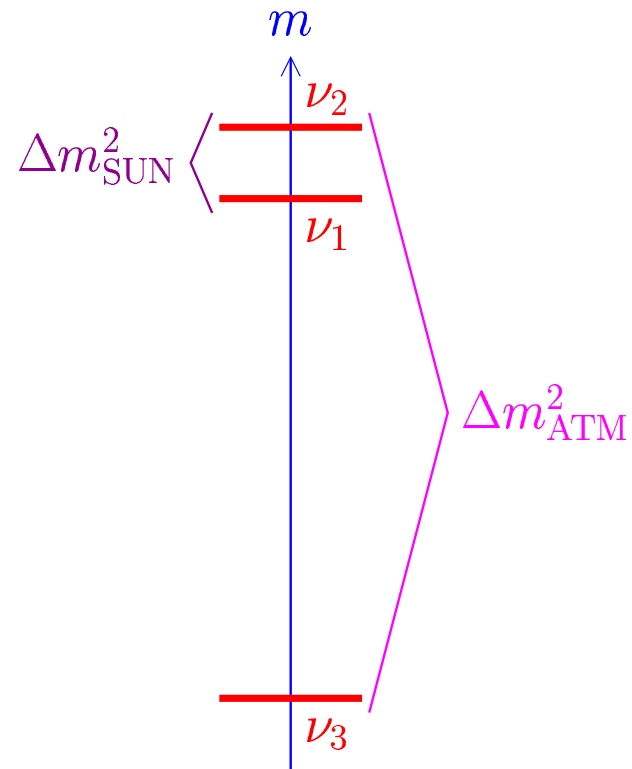
$$\Delta m_{\text{SUN}}^2 = \Delta m_{21}^2 \simeq 8.2 \times 10^{-5} \text{ eV}^2$$

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

Allowed Three-Neutrino Schemes



"normal"



"inverted"

absolute scale is not determined by neutrino oscillation data

Standard Parameterization of Mixing Matrix

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

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

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

$\vartheta_{23} \simeq \vartheta_{\text{ATM}}$
 $\vartheta_{13} = \vartheta_{\text{CHOOZ}}$
 $\vartheta_{12} = \vartheta_{\text{SUN}}$

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

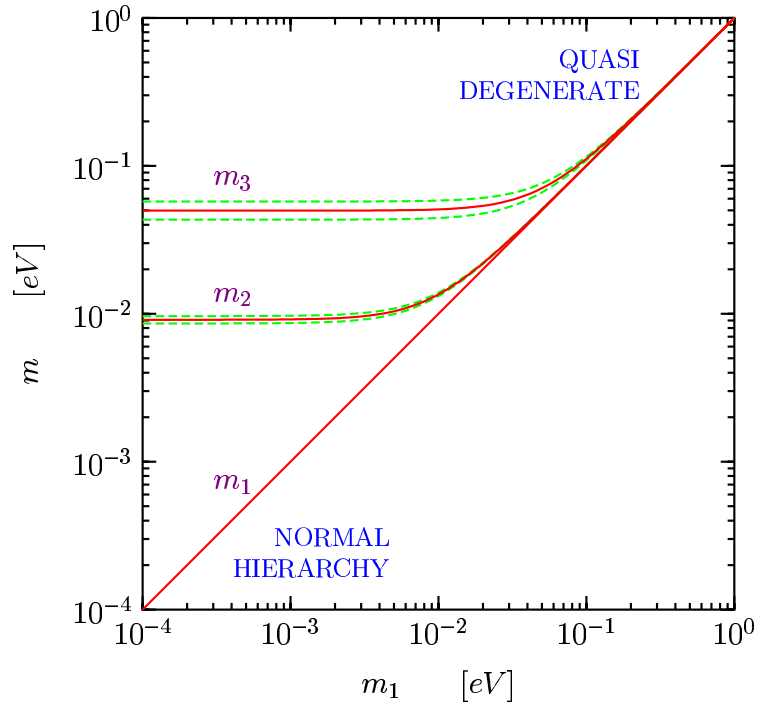
Global Fit of Oscillation Data \Rightarrow Bilinear Mixing

$$|U|_{\text{bf}} \simeq \begin{pmatrix} 0.84 & 0.53 & 0.10 \\ 0.31 - 0.43 & 0.56 - 0.63 & 0.71 \\ 0.32 - 0.44 & 0.57 - 0.64 & 0.70 \end{pmatrix}$$

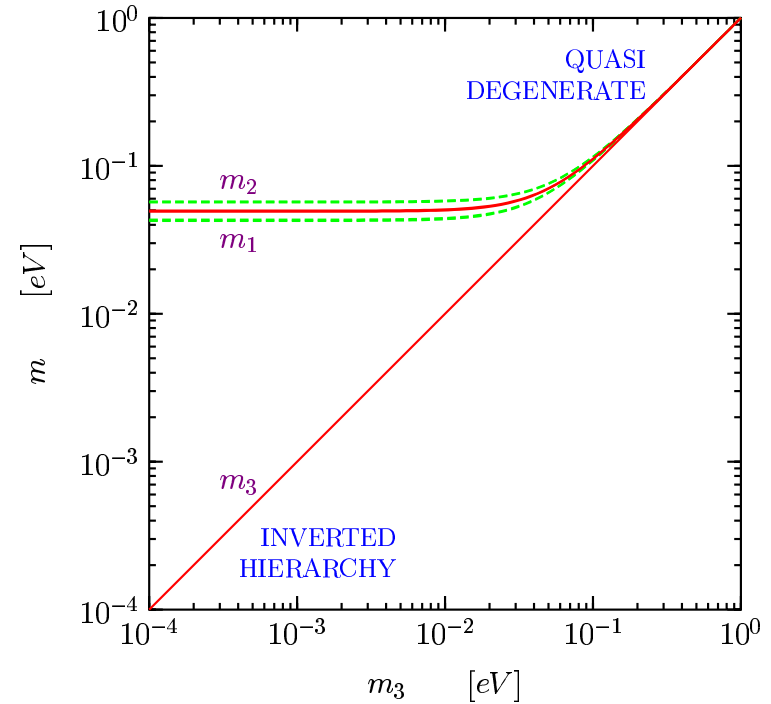
$$|U|_{3\sigma} \simeq \begin{pmatrix} 0.77 - 0.88 & 0.46 - 0.61 & 0.00 - 0.22 \\ 0.08 - 0.60 & 0.30 - 0.79 & 0.55 - 0.85 \\ 0.10 - 0.61 & 0.33 - 0.81 & 0.51 - 0.83 \end{pmatrix}$$

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 $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gg \sqrt{\Delta m_{\text{ATM}}^2} \simeq 5 \times 10^{-2} \text{ eV}$

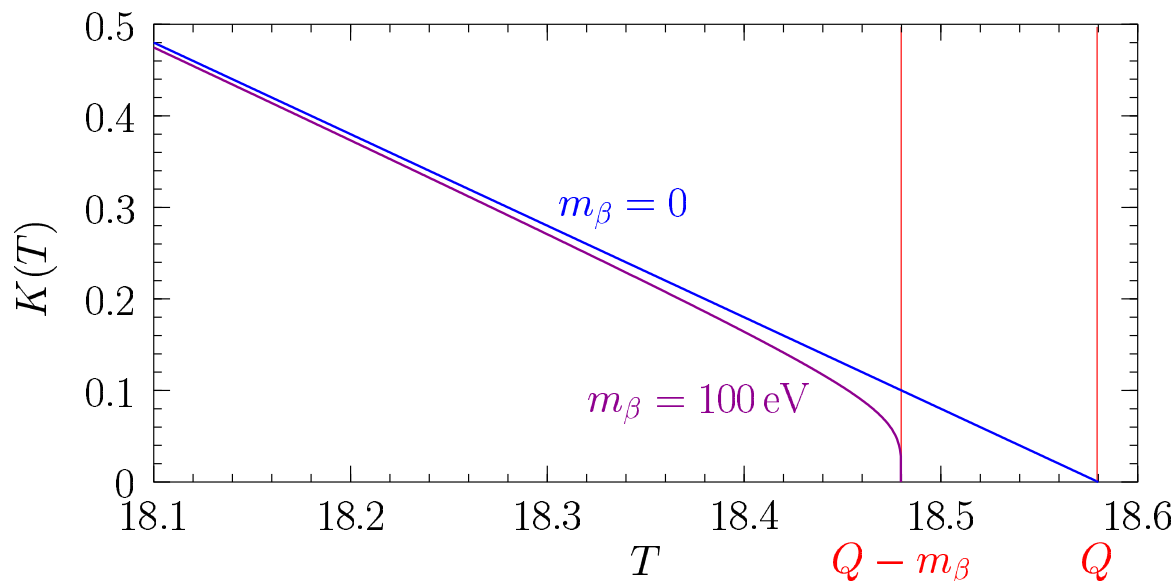
Tritium β Decay

$$\underline{{}^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e} \quad \frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E) pE (Q - T) \sqrt{(Q - T)^2 - m_\beta^2}$$

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

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

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



$$m_\beta < 2.2 \text{ eV} \quad (95\% \text{ C.L.})$$

Mainz & Troitsk

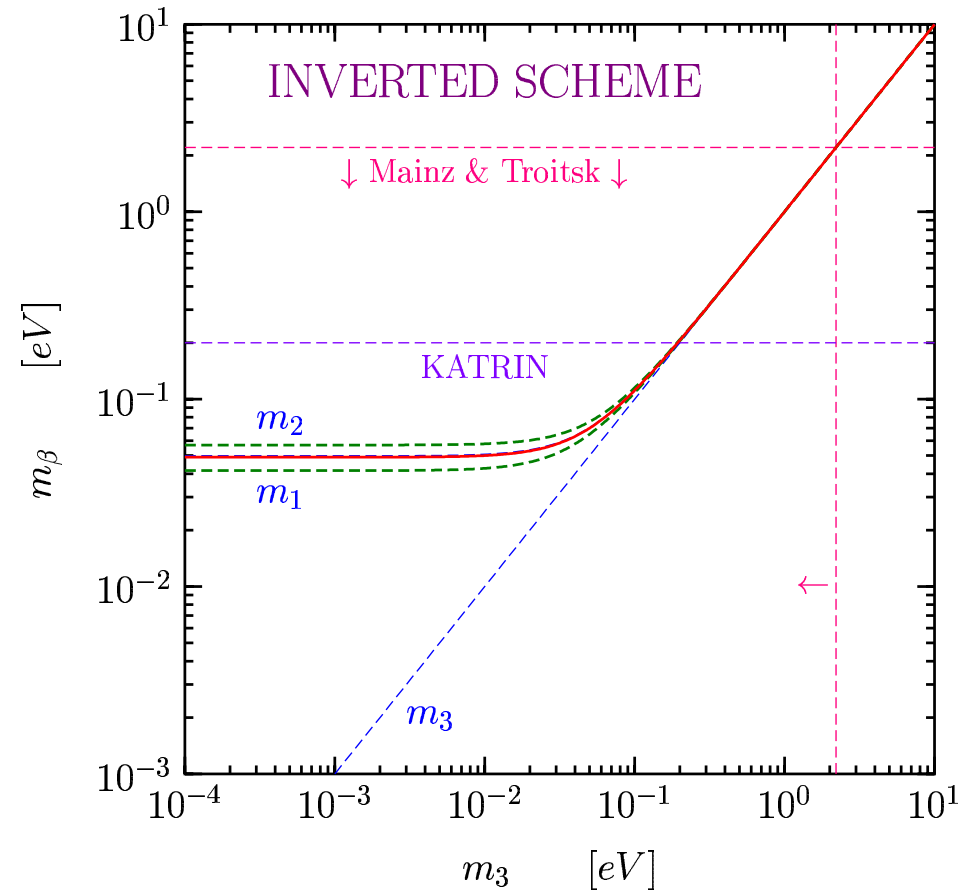
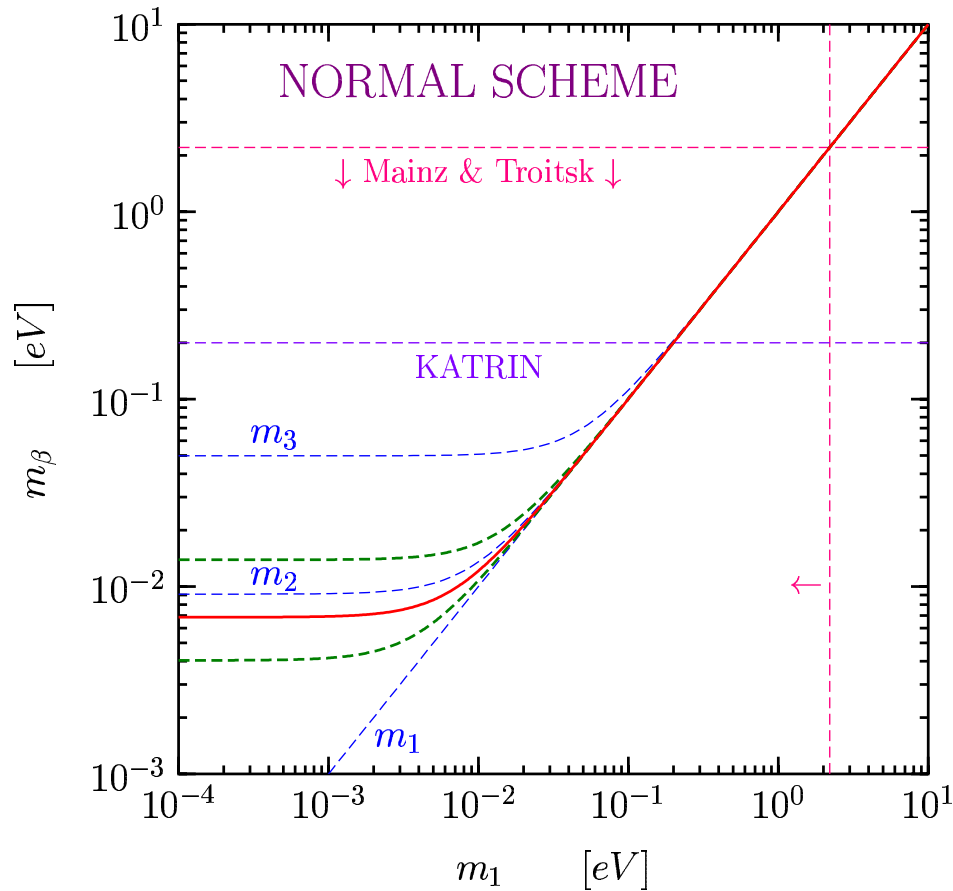
[Weinheimer, hep-ex/0210050]

future: KATRIN

[hep-ex/0109033]

[hep-ex/0309007]

sensitivity: $m_\beta \simeq 0.2 - 0.3 \text{ eV}$



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

Cosmological Bound on Neutrino Masses

neutrinos are in equilibrium in primeval plasma through weak interaction reactions



weak interactions freeze out

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

neutrino decoupling

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

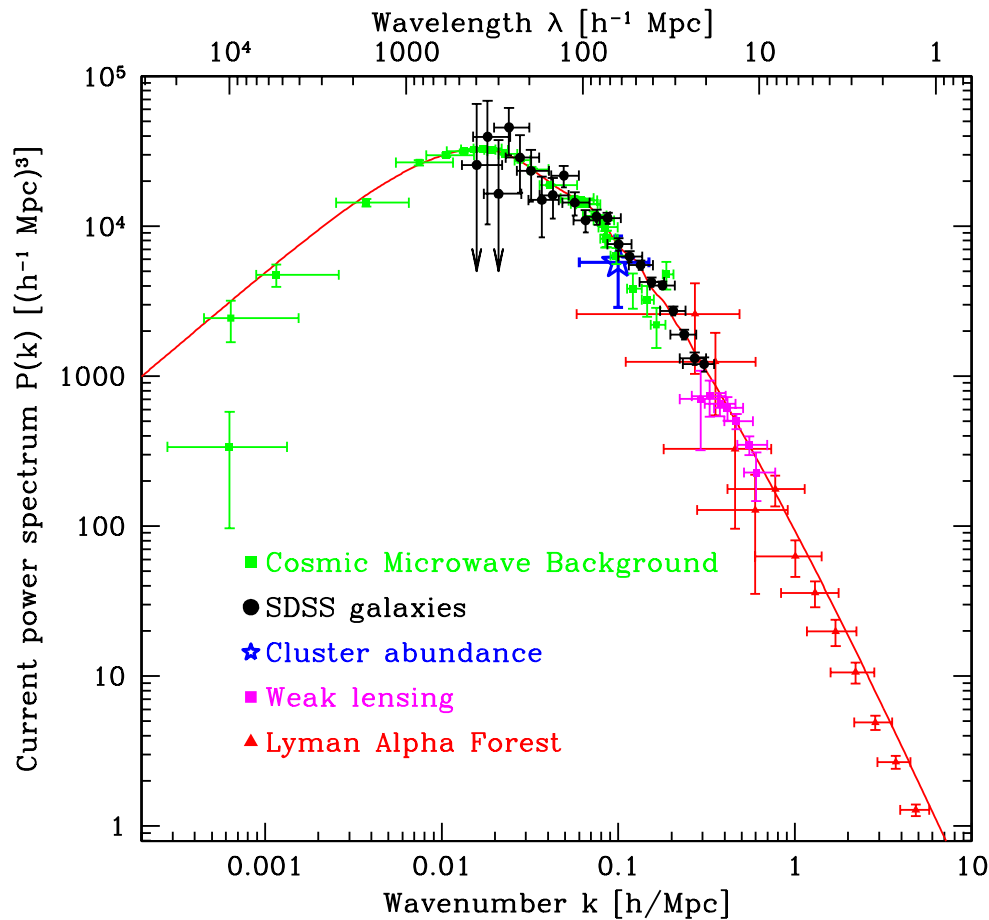
number density: $n_f = \frac{3}{4} \frac{\zeta(3)}{\pi^2} g_f T_f^3 \implies n_{\nu_k, \bar{\nu}_k} \simeq 0.1827 T_\nu^3 \simeq 112 \text{ cm}^{-3}$

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

($\rho_c = \frac{3H^2}{8\pi G_N}$) [Gershtein, Zeldovich, JETP Lett. 4 (1966) 120] [Cowsik, McClelland, PRL 29 (1972) 669]

$$h \sim 0.7, \quad \Omega_\nu \lesssim 1 \quad \implies \quad \sum_k m_k \lesssim 46 \text{ eV}$$

Power Spectrum of Density Fluctuations



[SDSS, astro-ph/0310725]

hot dark matter
prevents early galaxy formation

small scale suppression

$$\frac{\Delta P(k)}{P(k)} \approx -8 \frac{\Omega_\nu}{\Omega_m}$$

$$\approx -0.8 \left(\frac{\sum_k m_k}{1 \text{ eV}} \right) \left(\frac{0.1}{\Omega_m h^2} \right)$$

for

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

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

[Dolgov, PRep 370 (2002) 33] [Kainulainen, Olive, hep-ph/0206163] [Sarkar, hep-ph/0302175] [Hannestad, NJP 6 (2004) 108]

WMAP, AJ SS 148 (2003) 175

CMB (WMAP, CBI, ACBAR) + LSS (2dFGRS) + Ly α + HST + SN-Ia

Λ CDM

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

$$\Omega_{\text{tot}} = 1.02 \pm 0.02 \quad \Omega_b h^2 = 0.0224 \pm 0.0009 \quad \Omega_m h^2 = 0.135^{+0.008}_{-0.009}$$

$$\Omega_\nu h^2 < 0.0076 \quad (95\% \text{ conf.}) \quad \Rightarrow \quad \sum_k m_k < 0.71 \text{ eV}$$

Hannestad, JCAP 0305 (2003) 004

$$\sum_k m_k < 1.01 \text{ eV} \quad (95\% \text{ conf.}) \quad \text{WMAP+CBI+2dFGRS+HST+SN-Ia}$$

$$\sum_k m_k < 1.20 \text{ eV} \quad (95\% \text{ conf.}) \quad \text{WMAP+CBI+2dFGRS}$$

$$\sum_k m_k < 2.12 \text{ eV} \quad (95\% \text{ conf.}) \quad \text{WMAP+2dFGRS}$$

Elgaroy and Lahav, JCAP 04 (2003) 004

$$\sum_k m_k < 1.1 \text{ eV} \quad (95\% \text{ conf.}) \quad \text{WMAP+2dFGRS+HST}$$

SDSS, PRD 69 (2004) 103501

CMB(WMAP)+LSS(SDSS)+SN-Ia

$$h = 0.70_{-0.03}^{+0.04} \quad \Omega_m = 0.30 \pm 0.04 \quad \sum_k m_k < 1.7 \text{ eV} \quad (95\% \text{ conf.})$$

SDSS, astro-ph/0406594

CMB(WMAP)+LSS(SDSS)+bias(SDSS) $P_g(k) = b^2 P_m(k)$

$$\Omega_m = 0.25 \pm 0.03 \quad \sum_k m_k < 0.54 \text{ eV} \quad (95\% \text{ conf.})$$

SDSS, astro-ph/0407372

CMB(WMAP)+LSS(SDSS)+bias(SDSS)+Ly α (SDSS)+SN-Ia

$$\Omega_\Lambda = 0.72 \pm 0.02 \quad \sum_k m_k < 0.42 \text{ eV} \quad (95\% \text{ conf.})$$

Fogli, Lisi, Marrone, Melchiorri, Palazzo, Serra, Silk, hep-ph/0408045

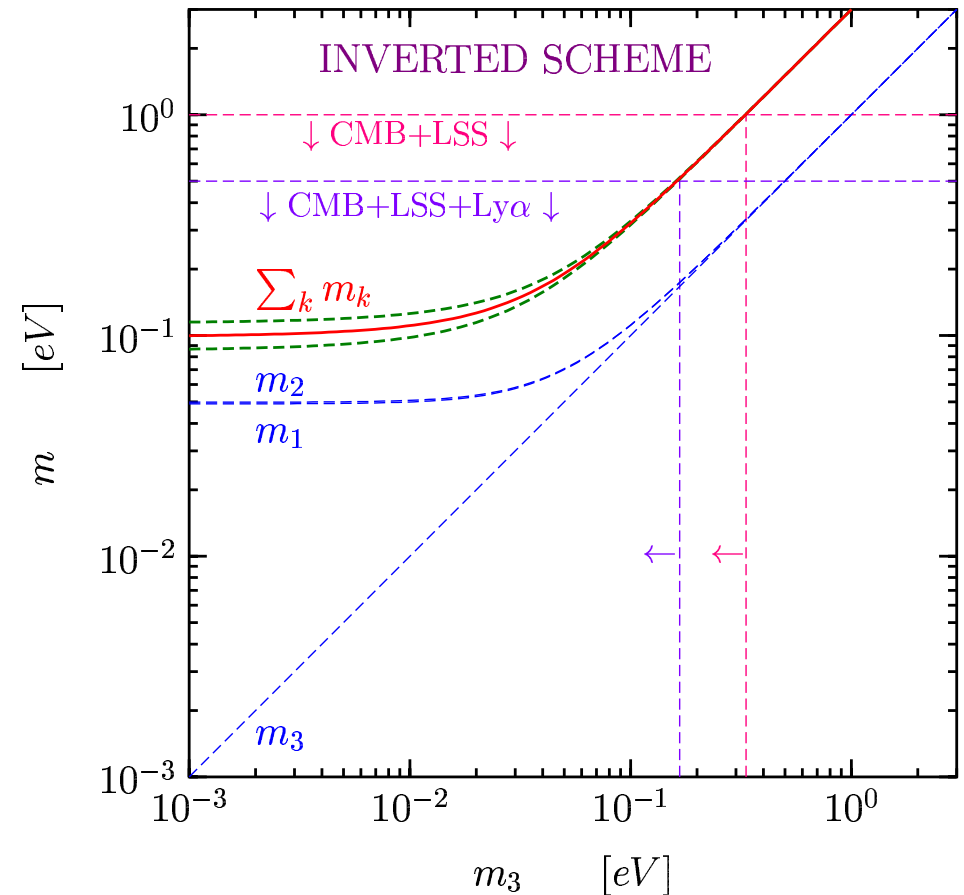
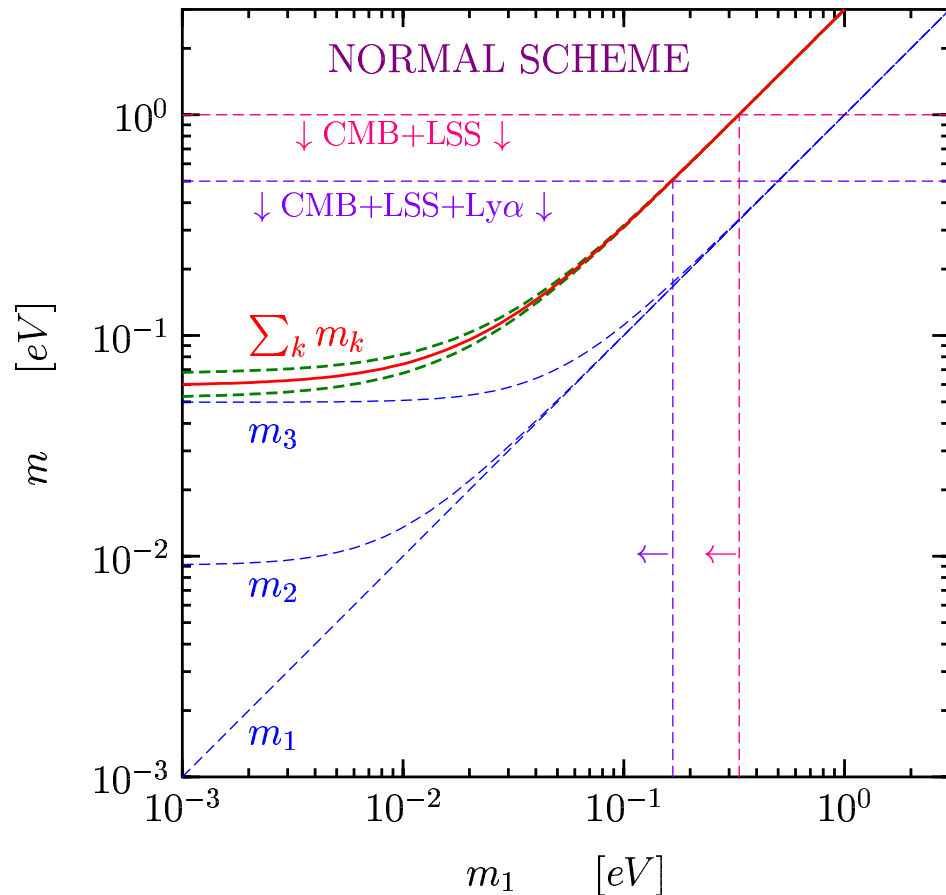
$$\begin{array}{lll} \sum_k m_k < 1.4 \text{ eV} & (2\sigma) & \text{CMB+LSS+HST+SN-Ia} \\ \sum_k m_k < 0.47 \text{ eV} & (2\sigma) & \text{CMB+LSS+HST+SN-Ia+Ly}\alpha\text{(SDSS)} \end{array}$$

$$\sum_k m_k \lesssim 1 \text{ eV} \quad (\sim 2\sigma)$$

$$\sum_k m_k \lesssim 0.5 \text{ eV} \quad (\sim 2\sigma)$$

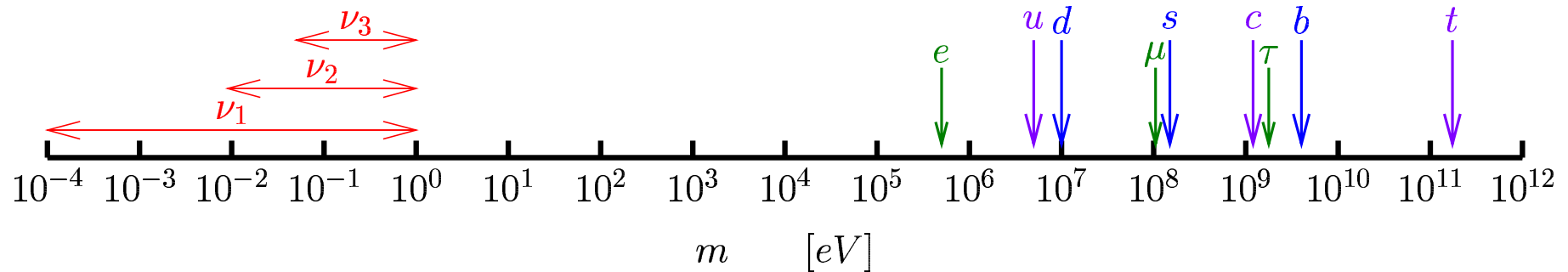
CMB+LSS+HST+SN-Ia

CMB+LSS+HST+SN-Ia+Ly α



FUTURE: IF $\sum_k m_k \lesssim 8 \times 10^{-2} \text{ eV} \implies$ NORMAL HIERARCHY

Majorana Neutrino Mass?



known natural explanations
of smallness of ν masses

- See-Saw Mechanism
- 5-D Non-Renormaliz. Eff. Operator

both imply

- Majorana ν masses $\iff |\Delta L| = 2 \iff \beta\beta_{0\nu}$ decay
- see-saw type relation $m_\nu \sim \frac{\mathcal{M}_{EW}^2}{\mathcal{M}}$
- new high energy scale \mathcal{M}

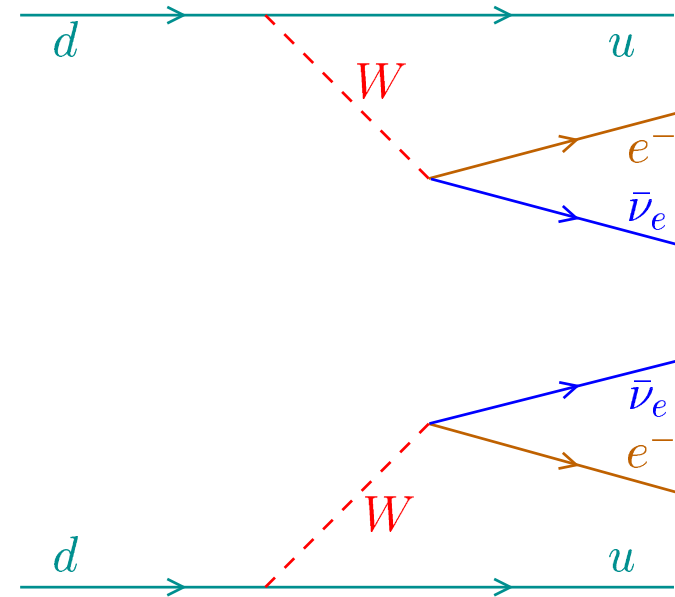
Majorana neutrino masses provide the most accessible window on New Physics Beyond the Standard Model

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

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

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

second order weak interaction process
in the Standard Model



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

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

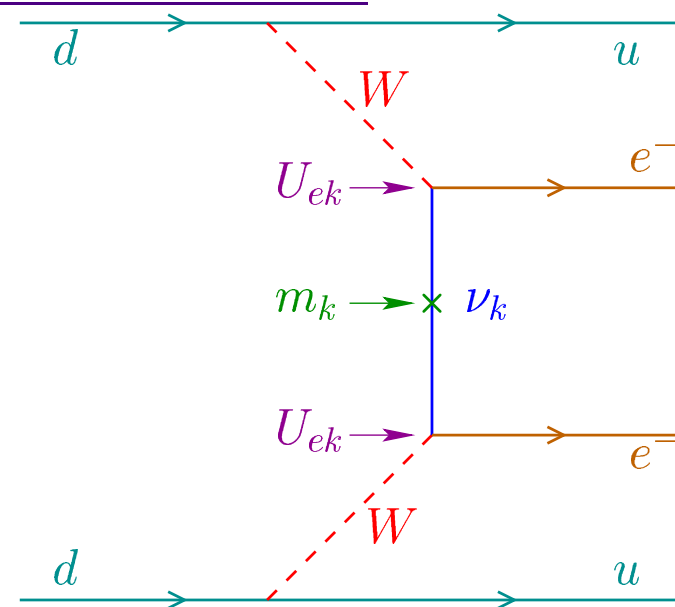
$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 |m_{\beta\beta}|^2$$

effective

Majorana

mass

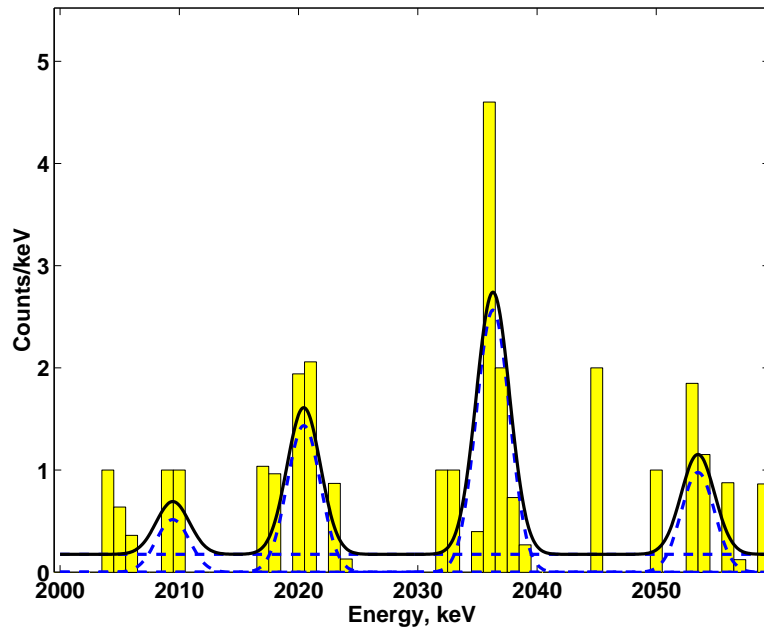
$$m_{\beta\beta} = \sum_k U_{ek}^2 m_k$$



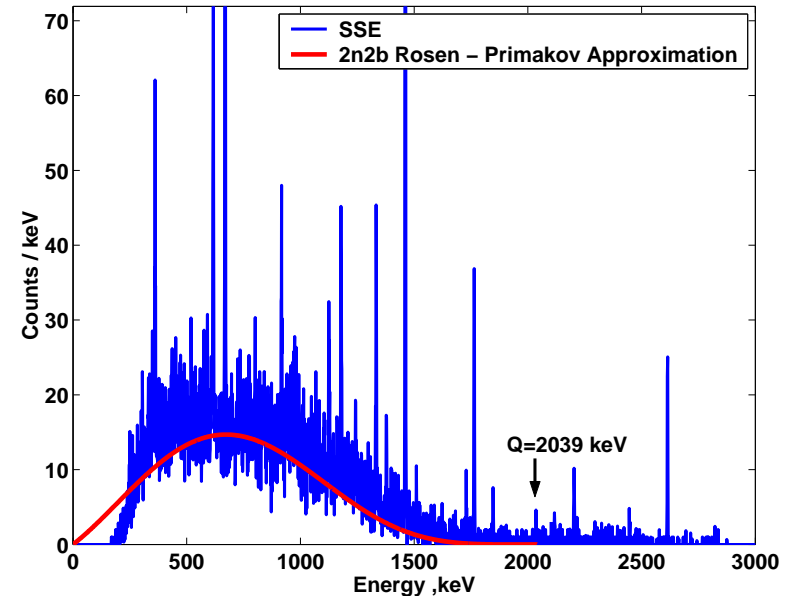
Indication of $\beta\beta_{0\nu}$ Decay

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

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



pulse-shape selected spectrum



3.8 σ evidence

[PLB 586 (2004) 198]

the indication must be checked by other experiments

$$1.35 \lesssim |\mathcal{M}_{0\nu}| \lesssim 4.12 \implies 0.22 \text{ eV} \lesssim |m_{\beta\beta}| \lesssim 1.6 \text{ eV}$$

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

Best limits for $\beta\beta_{0\nu}$ Decay

Heidelberg-Moscow

^{76}Ge

[EPJA 12 (2001) 147]

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

IGEX

^{76}Ge

[PRD 65 (2002) 092007]

$$T_{1/2}^{0\nu} > 1.57 \times 10^{25} \text{ y} \quad (90\% \text{ C.L.}) \implies |m_{\beta\beta}| \lesssim 0.35 - 1.1 \text{ eV}$$

FUTURE EXPERIMENTS

NEMO3, CUORICINO, COBRA, XMASS, CAMEO, CANDLES

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

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

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

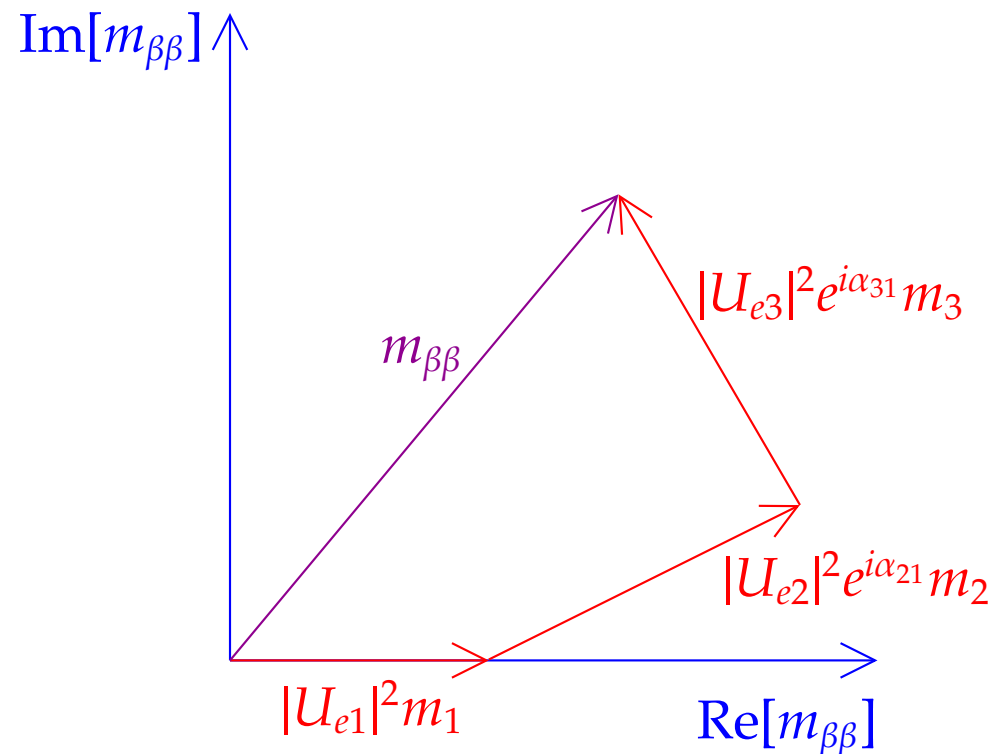
[Zdesenko, RMP 74 (2002) 663] [Elliott,Vogel, ARNPS 52 (2002) 115] [Elliott, Engel, JPG 30 (2004) R183]

Effective Majorana Neutrino Mass in $\beta\beta_{0\nu}$ Decay

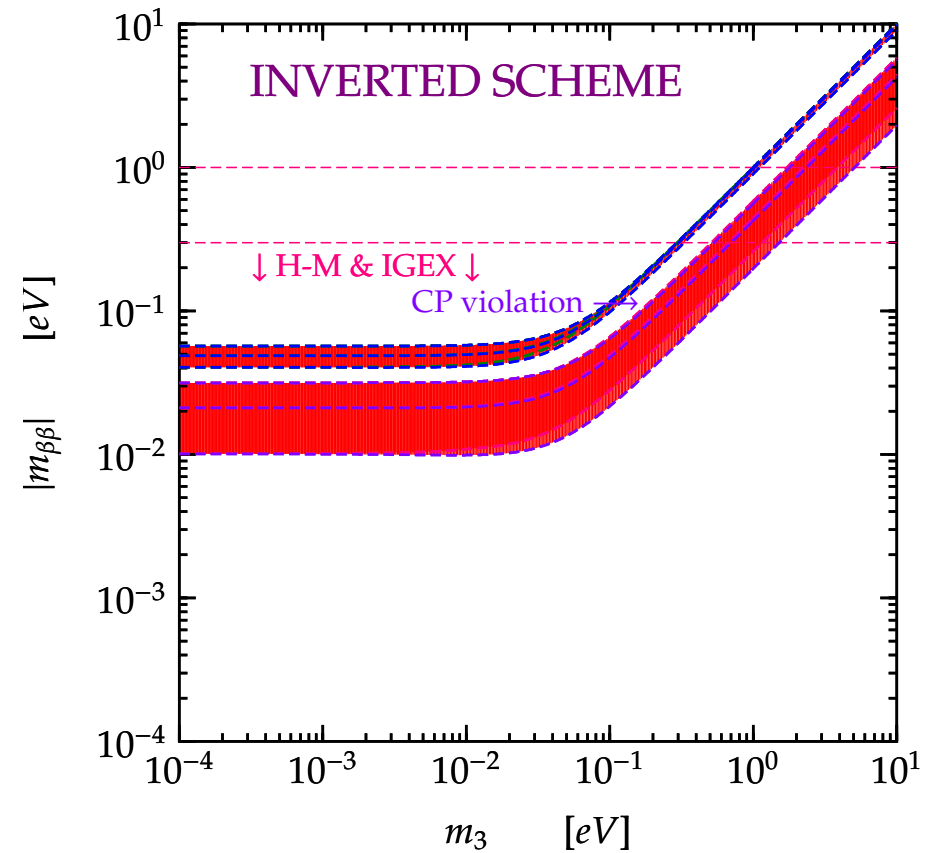
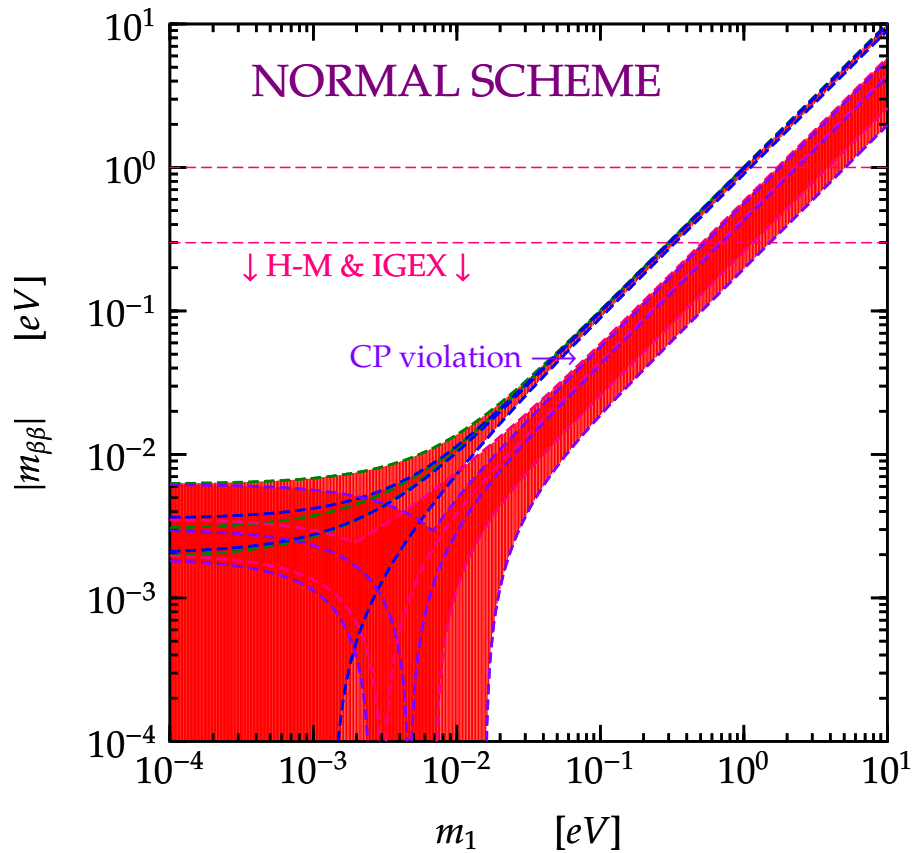
$$m_{\beta\beta} = \sum_k U_{ek}^2 m_k$$

complex $U_{ek} \Rightarrow$ possible cancellations

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



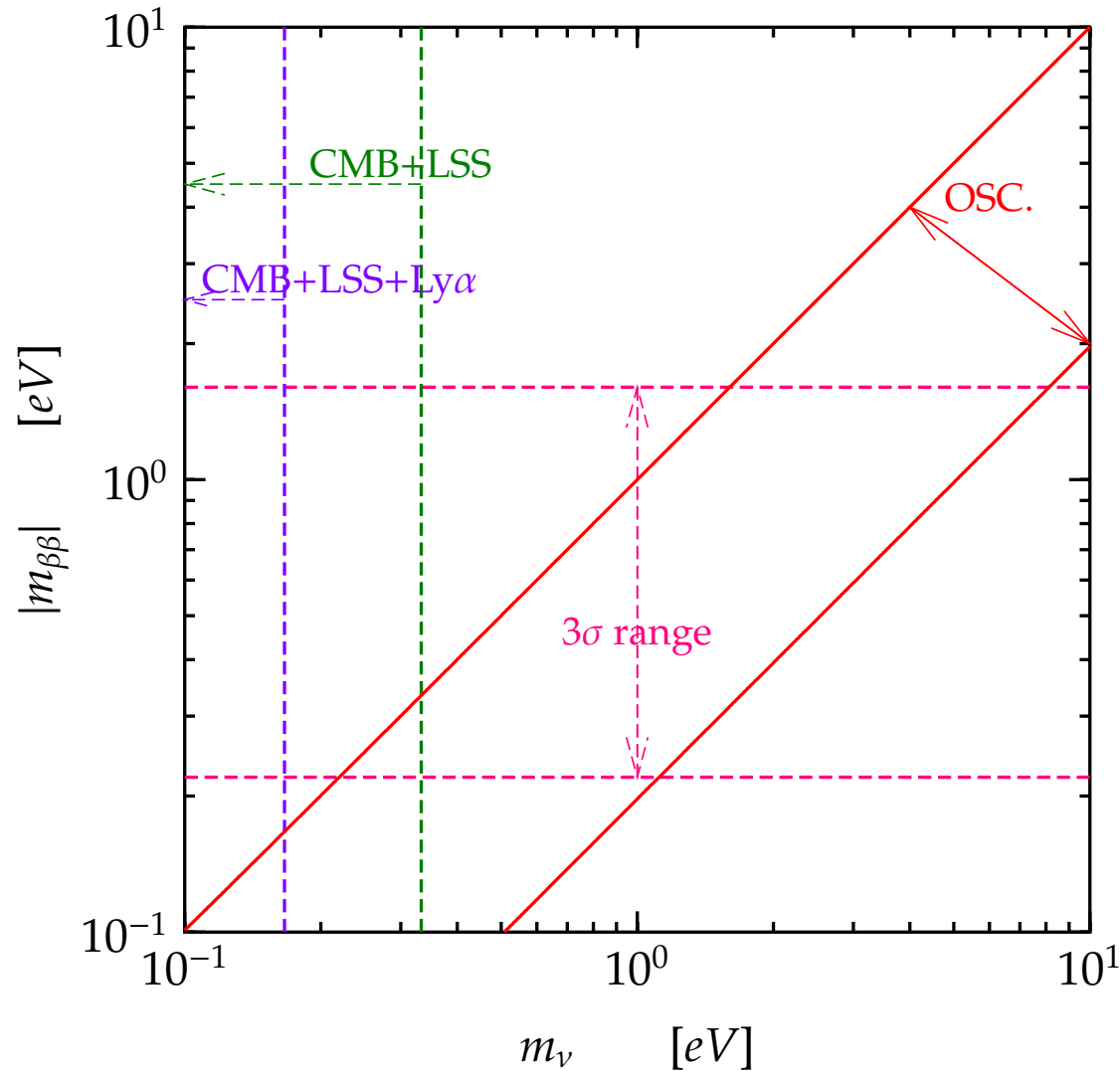
General Neutrino Oscillations Bounds for $\beta\beta_{0\nu}$ Decay



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

Indication of $\beta\beta_{0\nu}$ Decay

$$0.22 \text{ eV} \lesssim |m_{\beta\beta}| \lesssim 1.6 \text{ eV} \quad (3\sigma \text{ range})$$



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

Summary

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

$\nu_\mu \rightarrow \nu_\tau$ with $\Delta m_{\text{ATM}}^2 \simeq 2.4 \times 10^{-3} \text{ eV}^2$ (atmospheric ν , K2K)



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

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

FUTURE

Theory: Why lepton mixing \neq quark mixing?

Why only $|U_{e3}|^2 \ll 1$?

Exp.: Measure $|U_{e3}| > 0 \implies$ CP violation

Check $\beta\beta_{0\nu}$ signal at Quasi Degenerate mass scale

Improve bounds from β Decay, Cosmology, $\beta\beta_{0\nu}$ Decay