Neutrino Masses in Particle Physics and Cosmology

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Meeting in Honor of Samoil Bilenky's 80 Years

Barcelona, Park Guell by Antoni Gaudi, November 2002

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Outline

- Brief Introduction to Neutrino Masses and Mixing
- Three-Neutrino Mixing
- Absolute Scale of Neutrino Masses
- Conclusions

Brief Introduction to Neutrino Masses and Mixing

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  - Standard Model: Massless Neutrinos
  - Extension of the SM: Massive Neutrinos
  - Lepton Numbers
  - Two-Neutrino Mixing and Oscillations
- Three-Neutrino Mixing
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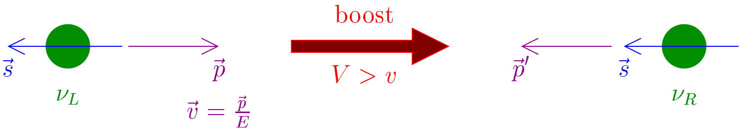
Standard Model: Massless Neutrinos



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

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

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

$(\nu^c)_R \equiv \nu_R \quad \Longrightarrow \quad$ Majorana mass term

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

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 $(e_L, e_R;\ u_L, u_R;\ d_L, d_R;\ \ldots)$

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

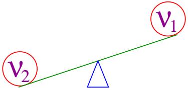
surprise: Majorana neutrino mass for ν_R is allowed! $\quad \mathcal{L}^{\mathrm{M}}_R \sim m^{\mathrm{M}}_R \overline{(\nu^c)_L} \nu_R$

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 light neutrino masses

massive neutrinos are Majorana!

3-GEN $\Rightarrow$ effective low-energy 3-ν mixing

[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
$(\nu_e\,,\,e^-)$	$+1$	0	0
$(\nu_\mu\,,\,\mu^-)$	0	$+1$	0
$(\nu_\tau\,,\,\tau^-)$	0	0	$+1$

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

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

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

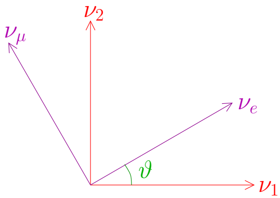
L_e, L_μ, L_τ are not conserved, but L is conserved $L(\nu_{\alpha R}) = L(\nu_{\beta L}) \Rightarrow |\Delta L| = 0$

Majorana mass term $m^{\mathrm{M}}\overline{\nu_L}(\nu^c)_R \to \begin{pmatrix}\overline{\nu_{eL}} & \overline{\nu_{\mu L}} & \overline{\nu_{\tau L}}\end{pmatrix} \begin{pmatrix} m^{\mathrm{M}}_{ee} & m^{\mathrm{M}}_{e\mu} & m^{\mathrm{M}}_{e\tau} \\ m^{\mathrm{M}}_{\mu e} & m^{\mathrm{M}}_{\mu\mu} & m^{\mathrm{M}}_{\mu\tau} \\ m^{\mathrm{M}}_{\tau e} & m^{\mathrm{M}}_{\tau\mu} & m^{\mathrm{M}}_{\tau\tau} \end{pmatrix} \begin{pmatrix}(\nu^c_e)_R \\ (\nu^c_\mu)_R \\ (\nu^c_\tau)_R\end{pmatrix}$

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

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



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

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

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

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

Three-Neutrino Mixing

Experimental Evidences of Neutrino Oscillations

Solar $\nu_e \to \nu_\mu, \nu_\tau$	Homestake Kamiokande GALLEX/GNO & SAGE Super-Kamiokande SNO BOREXino	$\to$	$\Delta m^2_{\text{SOL}} \simeq (7.6 \pm 0.2) \times 10^{-5}\,\text{eV}^2$ $\tan^2\vartheta_{\text{SOL}} \simeq 0.47 \pm 0.06$
Reactor $\bar{\nu}_e$ disappearance	(KamLAND)		
Atmospheric $\nu_\mu \to \nu_\tau$	Kamiokande IMB Super-Kamiokande MACRO Soudan-2	$\to$	$\Delta m^2_{\text{ATM}} \simeq (2.4 \pm 0.1) \times 10^{-3}\,\text{eV}^2$ $\sin^2\vartheta_{\text{ATM}} \simeq 0.50 \pm 0.07$
Accelerator ν_μ disappearance	(K2K & MINOS)		

Two scales of Δm^2: $\Delta m^2_{\text{ATM}} \simeq 30\,\Delta m^2_{\text{SOL}}$

Large mixings: $\vartheta_{\text{ATM}} \simeq 45^\circ$, $\vartheta_{\text{SOL}} \simeq 34^\circ$

Three-Neutrino Mixing

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

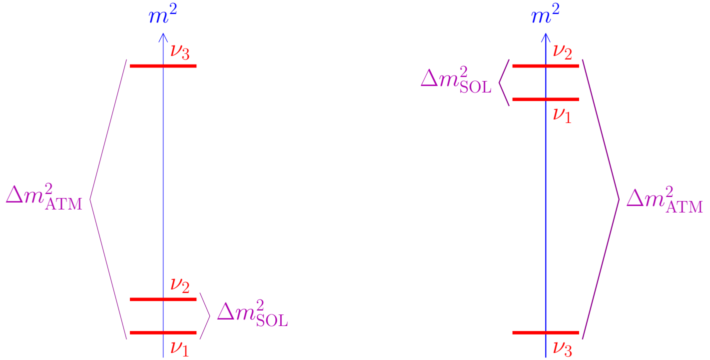
three flavor fields: ν_e, ν_μ, ν_τ

three massive fields: ν_1, ν_2, ν_3

$$\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq (7.6 \pm 0.2) \times 10^{-5} \, \text{eV}^2$$

$$\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq (2.4 \pm 0.1) \times 10^{-3} \, \text{eV}^2$$

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

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

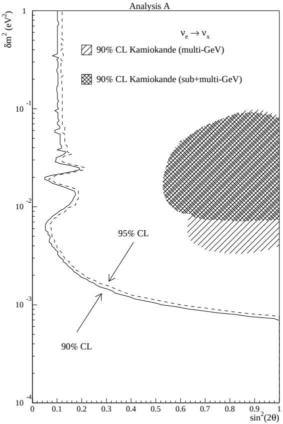
$$\begin{array}{rc} \text{SOL} \rightarrow & \\ U = & \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \\ & \qquad\qquad\quad \uparrow \\ & \qquad\qquad\quad \text{ATM} \end{array}$$

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

$$\Downarrow$$

$$\boxed{|U_{e3}|^2 \lesssim 5 \times 10^{-2}}$$

[Bilenky, Giunti, PLB 444 (1998) 379]



[CHOOZ, PLB 466 (1999) 415]

[Palo Verde, PRD 64 (2001) 112001]

SOLAR AND ATMOSPHERIC ν OSCILLATIONS ARE PRACTICALLY DECOUPLED!

TWO-NEUTRINO SOLAR and ATMOSPHERIC ν OSCILLATIONS ARE OK!

$$\sin^2\vartheta_{\text{SOL}} = \frac{|U_{e2}|^2}{1 - |U_{e3}|^2} \simeq |U_{e2}|^2 \qquad \sin^2\vartheta_{\text{ATM}} = |U_{\mu3}|^2$$

[Bilenky, Giunti, PLB 444 (1998) 379]

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

Bilarge Mixing

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

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

Global Analysis $\Longrightarrow$ $\sin^2\vartheta_{13} < 0.035$ (90% C.L.) [Schwetz et al, hep-ph/0808.2016]

$\sin^2\vartheta_{13} = 0.016 \pm 0.010$ [Fogli, Lisi, Marrone, Palazzo, Rotunno, PRL 101 (2008) 141801, hep-ph/0808.2016]

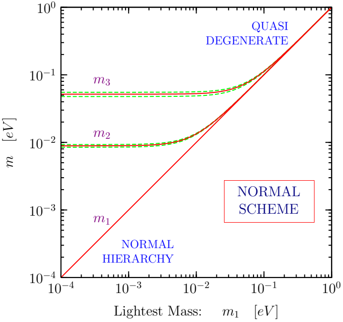
$\sin^2\vartheta_{13} = 0.014 \pm 0.008$ (Bayesian) [Ge, Giunti, Liu, hep-ph/0810.5443]

Absolute Scale of Neutrino Masses

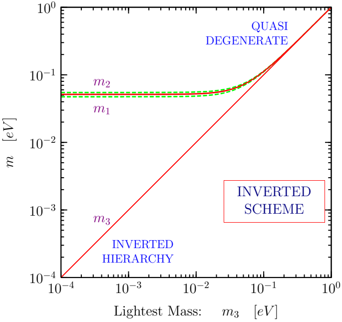
- Brief Introduction to Neutrino Masses and Mixing
- Three-Neutrino Mixing
- Absolute Scale of Neutrino Masses
  - Mass Hierarchy or Degeneracy?
  - Tritium Beta-Decay
  - Cosmological Bound on Neutrino Masses
  - Neutrinoless Double-Beta Decay
- Conclusions

Mass Hierarchy or Degeneracy?

normal scheme



inverted scheme



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

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

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

Tritium Beta-Decay

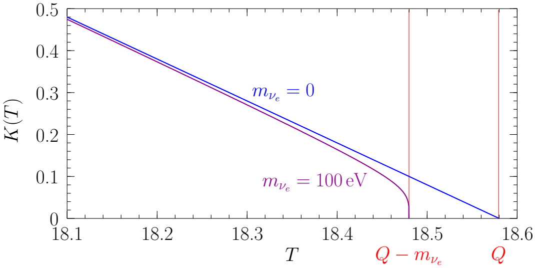
$^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$

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

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

Kurie plot

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



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

Mainz & Troitsk

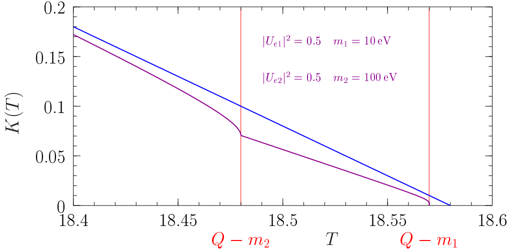
[Weinheimer, hep-ex/0210050]

future: KATRIN (start 2012)

[arXiv:0810.3281]

sensitivity: $m_{\nu_e} \simeq 0.2\,\mathrm{eV}$ (3y)

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



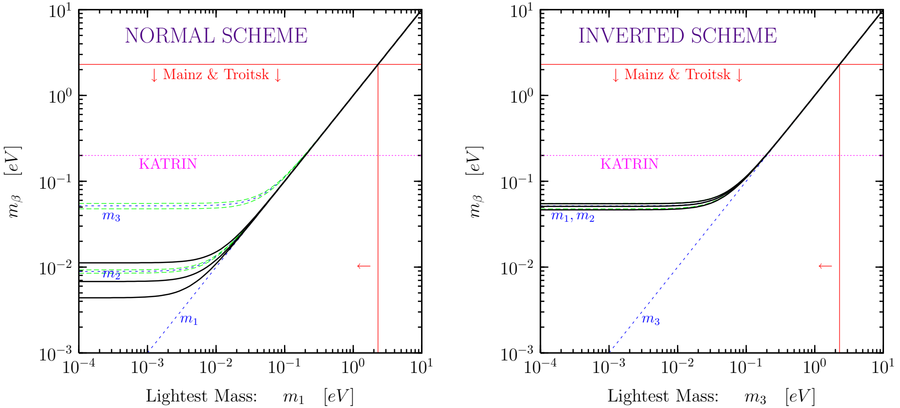
analysis of data is different from the no-mixing case: $2N-1$ parameters $\left(\sum_k |U_{ek}|^2 = 1 \right)$

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

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

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

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



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

Cosmological Bound on Neutrino Masses

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

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

neutrino decoupling

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

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

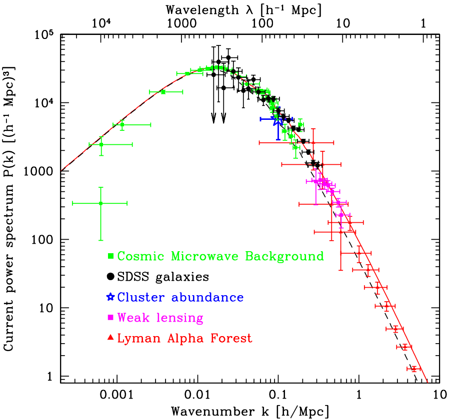
density contribution: $\Omega_k = \frac{n_{\nu_k,\bar{\nu}_k}\, m_k}{\rho_c} \simeq \frac{1}{h^2}\frac{m_k}{94.14\,\text{eV}} \Longrightarrow \boxed{\Omega_\nu h^2 = \frac{\sum_k m_k}{94.14\,\text{eV}}}$

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

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

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

Power Spectrum of Density Fluctuations



[Tegmark, hep-ph/0503257]

Solid Curve: flat ΛCDM model

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

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

hot dark matter
prevents early galaxy formation

$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x}) - \overline{\rho}}{\overline{\rho}}$$

$$\langle \delta(\vec{x}_1)\delta(\vec{x}_2) \rangle = \int \frac{d^3k}{(2\pi)^3}\, e^{i\vec{k}\cdot\vec{x}}\, P(\vec{k})$$

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

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

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

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

CMB (WMAP, ...) + LSS (2dFGRS) + HST + SN-Ia $\Longrightarrow$ Flat ΛCDM

$T_0 = 13.7 \pm 0.2\,\text{Gyr} \qquad h = 0.71^{+0.04}_{-0.03}$

$\Omega_0 = 1.02 \pm 0.02 \qquad \Omega_b = 0.044 \pm 0.004 \qquad \Omega_m = 0.27 \pm 0.04$

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

WMAP (Five Years), astro-ph/0803.0547

CMB + HST + SN-Ia + BAO

$$T_0 = 13.72 \pm 0.12\,\text{Gyr} \qquad h = 0.705 \pm 0.013$$

$$-0.0179 < \Omega_0 - 1 < 0.0081 \quad \text{(95\% C.L.)}$$

$$\Omega_b = 0.0456 \pm 0.0015 \qquad \Omega_m = 0.274 \pm 0.013$$

$$\sum_{k=1}^{3} m_k < 0.67\,\text{eV} \quad \text{(95\% C.L.)} \qquad N_{\text{eff}} = 4.4 \pm 1.5$$

Fogli, Lisi, Marrone, Melchiorri, Palazzo, Rotunno, Serra, Silk, Slosar

[PRD 78 (2008) 033010, hep-ph/0805.2517]

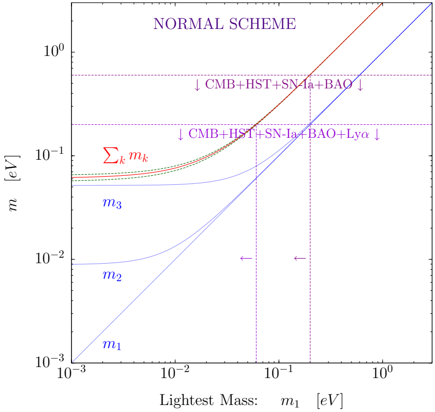
Flat ΛCDM

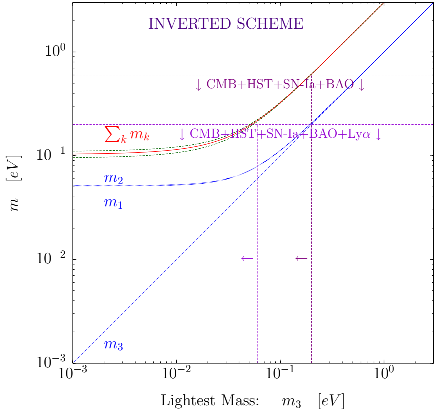
Case	Cosmological data set	Σ (at 2σ)
1	CMB	< 1.19 eV
2	CMB + LSS	< 0.71 eV
3	CMB + HST + SN-Ia	< 0.75 eV
4	CMB + HST + SN-Ia + BAO	< 0.60 eV
5	CMB + HST + SN-Ia + BAO + Lyα	< 0.19 eV

2σ (95% C.L.) constraints on the sum of ν masses Σ.

$$\sum_{k=1}^{3} m_k \lesssim 0.6\,\text{eV} \qquad (\sim 2\sigma) \qquad \text{CMB + HST + SN-Ia + BAO}$$

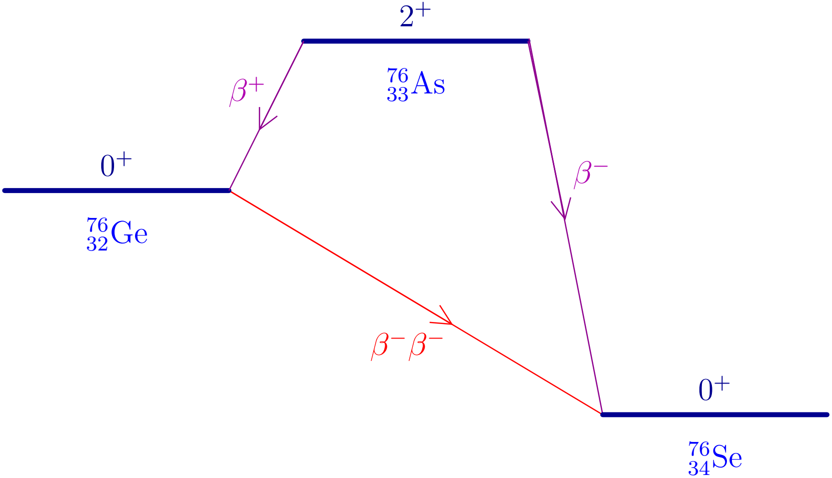
$$\sum_{k=1}^{3} m_k \lesssim 0.2\,\text{eV} \qquad (\sim 2\sigma) \qquad \text{CMB + HST + SN-Ia + BAO + Ly}\alpha$$





FUTURE: IF $\sum_{k=1}^{3} m_k \lesssim 9 \times 10^{-2}\,\text{eV} \Longrightarrow$ NORMAL HIERARCHY

Neutrinoless Double-Beta Decay



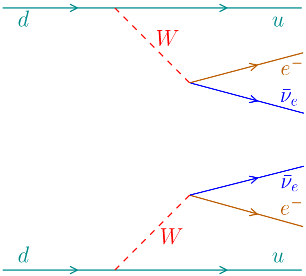
Effective Majorana Neutrino Mass: $$m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$$

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



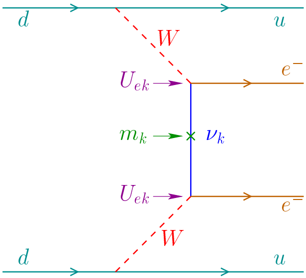
Neutrinoless Double-β Decay: $\Delta L = 2$

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

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

effective
Majorana
mass

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

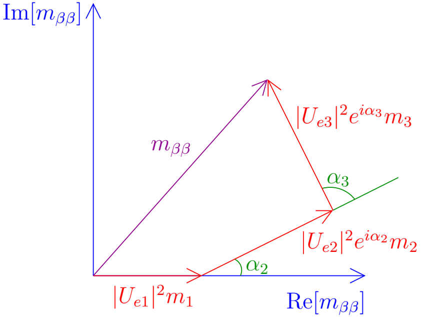


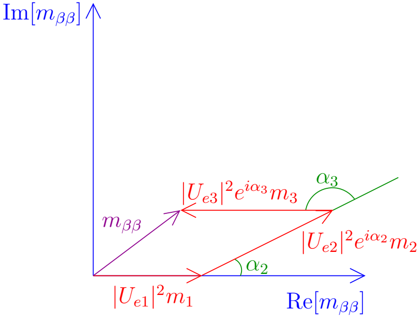
Effective Majorana Neutrino Mass

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

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

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





Experimental Bounds

CUORICINO (^{130}Te) [PRC 78 (2008) 035502]

$$\boxed{T^{0\nu}_{1/2} > 3 \times 10^{24}\,\text{y} \quad (90\%\ \text{C.L.})} \Longrightarrow \boxed{|m_{\beta\beta}| \lesssim 0.19 - 0.68\,\text{eV}}$$

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]

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

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

COBRA, XMASS, CAMEO, CANDLES

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

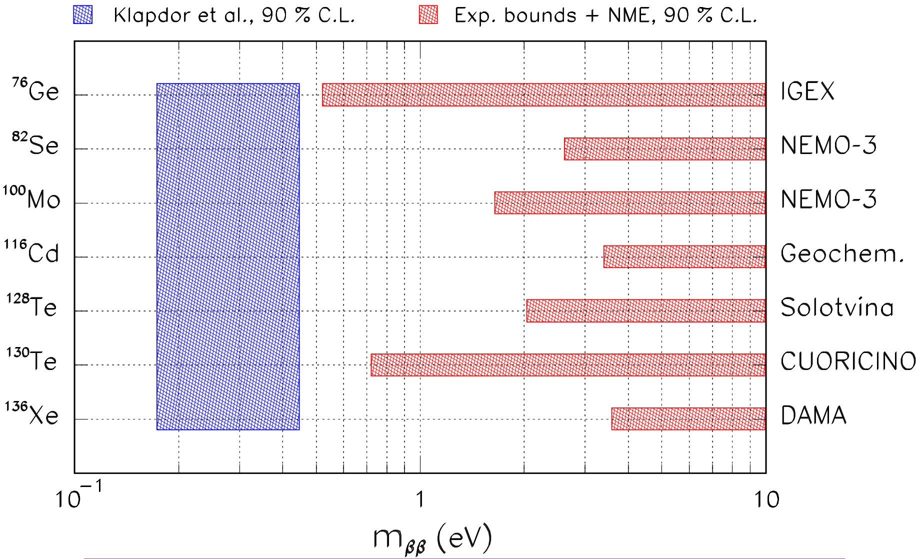
EXO, MOON, Super-NEMO, CUORE, Majorana, GEM, GERDA

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

Nuclear Matrix Element

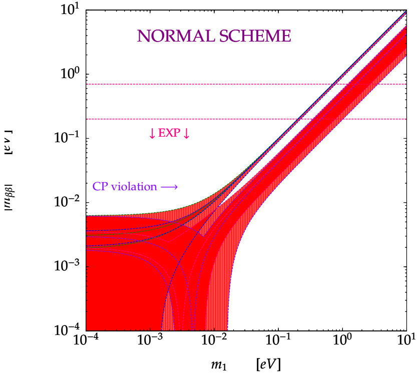
Faessler, Fogli, Lisi, Rodin, Rotunno, Simkovic

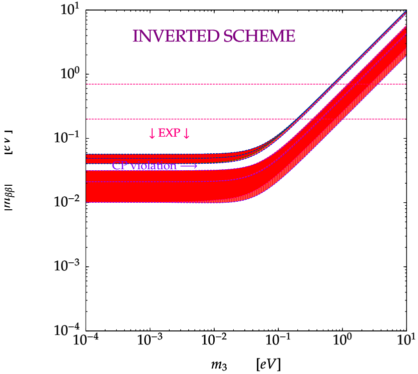
[hep-ph/0810.5733]



Bounds from Neutrino Oscillations

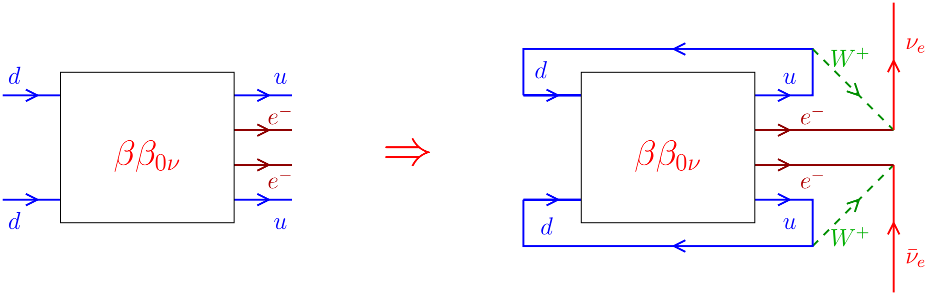
$$m_{\beta\beta} = |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_{21}}\, m_2 + |U_{e3}|^2\, e^{i\alpha_{31}}\, m_3$$





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

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



[Schechter, Valle, PRD 25 (1982) 2951] [Takasugi, PLB 149 (1984) 372]

Majorana Mass Term

$$\boxed{\mathcal{L}_L^{\mathrm{M}} = -\frac{1}{2}\, m \left(\overline{\nu_L^c}\, \nu_L + \overline{\nu_L}\, \nu_L^c \right) = \frac{1}{2}\, m \left(\nu_L^T\, \mathcal{C}^\dagger\, \nu_L + \nu_L^\dagger\, \mathcal{C}\, \nu_L^* \right)}$$

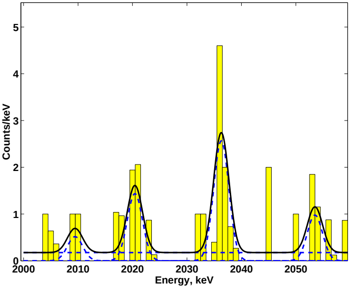
two conditions: $\begin{cases} u,\ d,\ e \text{ are massive} \\ \text{standard left-handed weak interaction exists} \end{cases}$

cancellation with other diagrams is very unlikely
(no symmetry, unstable under perturbative expansion)

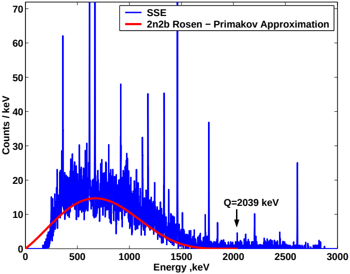
Experimental Positive Indication

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

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



pulse-shape selected spectrum



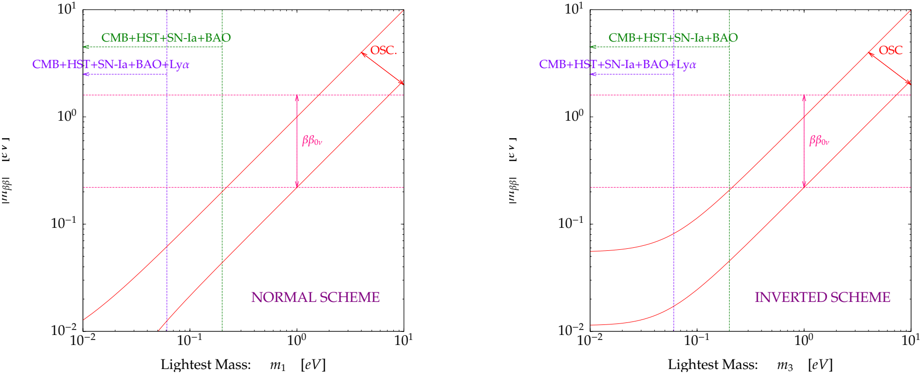
3.8σ evidence [PLB 586 (2004) 198]

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)

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+HST+SN-Ia+BAO(+Lyα) – $\beta\beta_{0\nu}$ signal

Conclusions

$\nu_e \to \nu_\mu, \nu_\tau$ with $\Delta m^2_{\text{SOL}} \simeq 8.3 \times 10^{-5}\,\text{eV}^2$ (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?

(Due to Majorana nature of ν's?)

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

Continue improvement of $\mathcal{M}_{0\nu}$ uncertainties.

Exp.: Measure $|U_{e3}| > 0 \Rightarrow$ CP viol., 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