Phenomenology of Light Sterile Neutrinos

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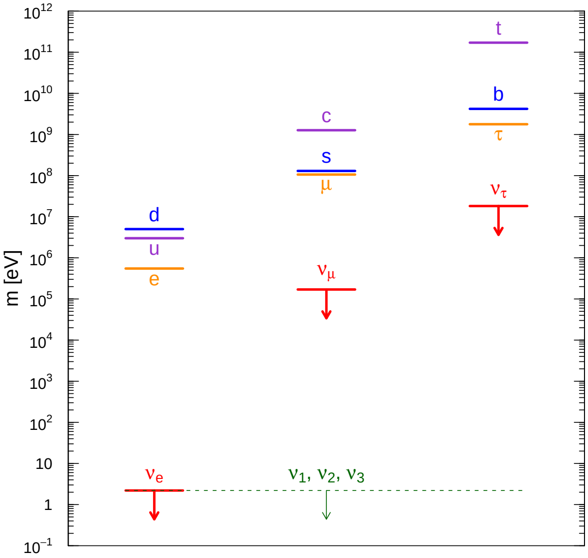
Fermion Mass Spectrum



Neutrino Oscillations

- 1957: Bruno Pontecorvo proposed Neutrino Oscillations in analogy with $K^0 \leftrightarrows \bar{K}^0$ oscillations (Gell-Mann and Pais, 1955)

- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions

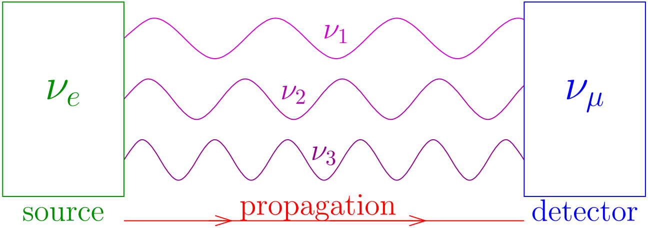
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector

- A Flavor Neutrino is a superposition of Massive Neutrinos

$$
\begin{aligned}
|\nu_e\rangle &= U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle \\
|\nu_\mu\rangle &= U_{\mu1}\,|\nu_1\rangle + U_{\mu2}\,|\nu_2\rangle + U_{\mu3}\,|\nu_3\rangle \\
|\nu_\tau\rangle &= U_{\tau1}\,|\nu_1\rangle + U_{\tau2}\,|\nu_2\rangle + U_{\tau3}\,|\nu_3\rangle
\end{aligned}
$$

- U is the 3×3 Neutrino Mixing Matrix

$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle$$



$$|\nu(t>0)\rangle = U_{e1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{e2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{e3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_e\rangle$$

at the detector there is a probability > 0 to see the neutrino as a ν_μ

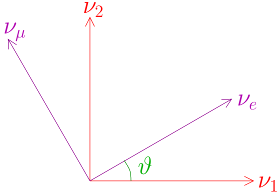
Neutrino Oscillations are Flavor Transitions

$$\nu_e \to \nu_\mu \qquad \nu_e \to \nu_\tau \qquad \nu_\mu \to \nu_e \qquad \nu_\mu \to \nu_\tau$$

$$\bar\nu_e \to \bar\nu_\mu \qquad \bar\nu_e \to \bar\nu_\tau \qquad \bar\nu_\mu \to \bar\nu_e \qquad \bar\nu_\mu \to \bar\nu_\tau$$

Two-Neutrino Mixing and Oscillations

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



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

$$|\nu_e\rangle = \cos\vartheta\, |\nu_1\rangle + \sin\vartheta\, |\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\vartheta\, |\nu_1\rangle + \cos\vartheta\, |\nu_2\rangle$$

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

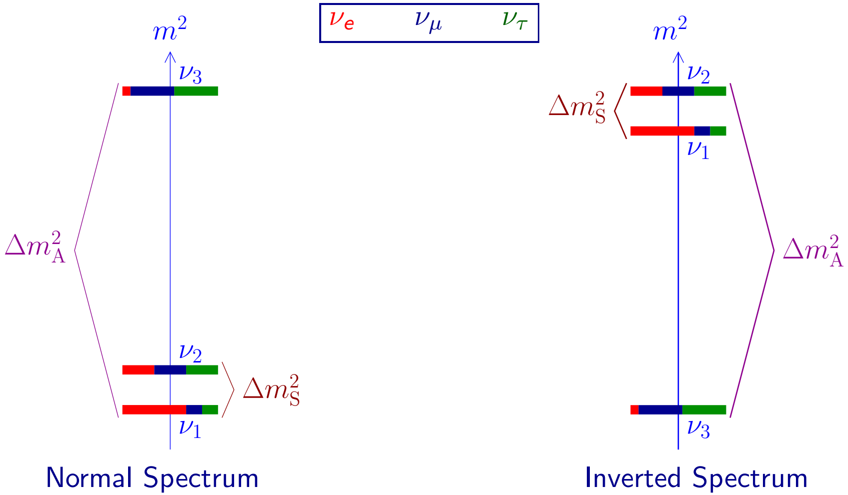
Transition Probability: $P_{\nu_e\to\nu_\mu} = P_{\nu_\mu\to\nu_e} = \sin^2 2\vartheta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

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

Experimental Evidences of Neutrino Oscillations

Solar $\nu_e \to \nu_\mu, \nu_\tau$	(SNO, BOREXino; Super-Kamiokande; GALLEX/GNO, SAGE; Homestake; Kamiokande)	$\to$ $\Delta m^2_{\mathrm{S}} \simeq 7.6 \times 10^{-5}\,\mathrm{eV}^2$, $\sin^2\vartheta_{\mathrm{S}} \simeq 0.30$
Reactor $\bar{\nu}_e$ disappearance	(KamLAND)	
Atmospheric $\nu_\mu \to \nu_\tau$	(Super-Kamiokande; Kamiokande; IMB, MACRO; Soudan-2)	$\to$ $\Delta m^2_{\mathrm{A}} \simeq 2.4 \times 10^{-3}\,\mathrm{eV}^2$, $\sin^2\vartheta_{\mathrm{A}} \simeq 0.50$
Accelerator ν_μ disappearance	(K2K, MINOS, T2K)	
Accelerator $\nu_\mu \to \nu_e$	(T2K, MINOS)	$\to$ Δm^2_{A}, $\sin^2\vartheta_{13} \simeq 0.023$
Reactor $\bar{\nu}_e$ disappearance	(Daya Bay, RENO; Double Chooz)	

Three-Neutrino Mixing Paradigm



$\Delta m^2_{\mathrm{S}} = \Delta m^2_{21}$ $\qquad$ $\Delta m^2_{\mathrm{A}} = |\Delta m^2_{31}| \simeq |\Delta m^2_{32}|$

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

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\vartheta_{23}=\vartheta_{\mathrm{A}}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix}}_{\text{Chooz, Palo Verde}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\vartheta_{12}=\vartheta_{\mathrm{S}}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}}_{\beta\beta_{0\nu}}$$

$\vartheta_{23} = \vartheta_{\mathrm{A}}$

$\sin^2\vartheta_{23} \simeq 0.4 - 0.6$

Chooz, Palo Verde

T2K, MINOS

Daya Bay, RENO

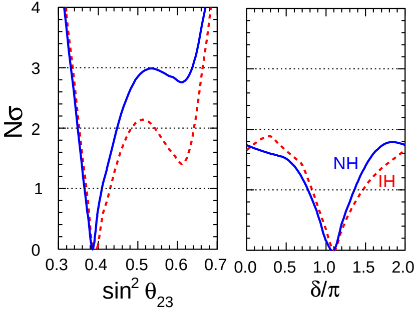
$\sin^2\vartheta_{13} = 0.023 \pm 0.002$

$\vartheta_{12} = \vartheta_{\mathrm{S}}$

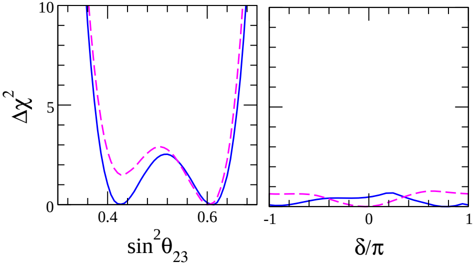
$\sin^2\vartheta_{12} = 0.30 \pm 0.01$

$\beta\beta_{0\nu}$

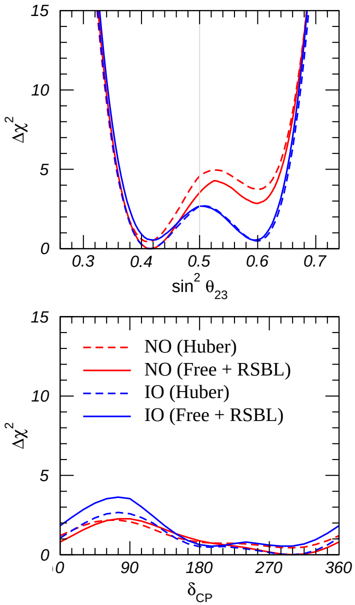
$$\frac{\delta\sin^2\vartheta_{23}}{\sin^2\vartheta_{23}} \simeq 40\% \qquad \frac{\delta\sin^2\vartheta_{13}}{\sin^2\vartheta_{13}} \simeq 10\% \qquad \frac{\delta\sin^2\vartheta_{12}}{\sin^2\vartheta_{12}} \simeq 5\%$$



[Fogli, Lisi, Marrone, Montanino, Palazzo, Rotunno, PRD 86 (2012) 013012]



[Forero, Tortola, Valle, PRD 86 (2012) 073012]

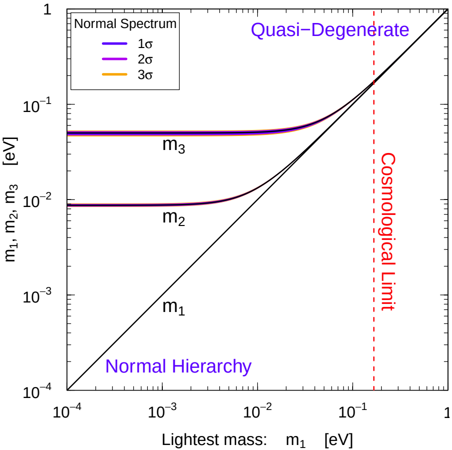


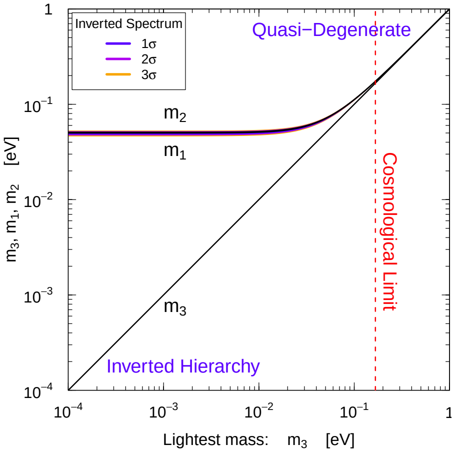
[Gonzalez-Garcia, Maltoni, Salvado, Schwetz, JHEP 12 (2012) 123; `http://www.nu-fit.org`]

Open Problems

- $\vartheta_{23} < 45^{\circ}$?
  - Atmospheric Neutrinos, T2K, NOνA, ...
- CP violation ?
  - NOνA, LAGUNA, CERN-GS, HyperK, ...
- Mass Hierarchy ?
  - NOνA, Atmospheric Neutrinos, Day Bay II, Supernova Neutrinos, ...
- Absolute Mass Scale ?
  - β Decay, Neutrinoless Double-β Decay, Cosmology, ...
- Dirac or Majorana ?
  - Neutrinoless Double-β Decay, ...
- Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

Absolute Scale of Neutrino Masses





$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_S^2$$
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$

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

Quasi-Degenerate for $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gtrsim \sqrt{\Delta m_A^2} \simeq 5 \times 10^{-2}\,\text{eV}$

Tritium Beta-Decay

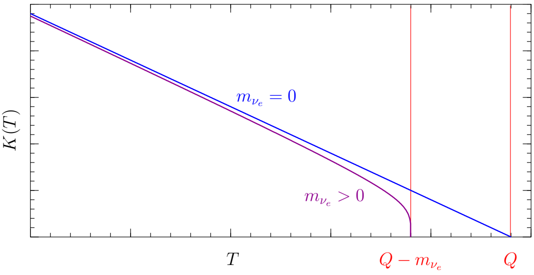
$^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_e$

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

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

Kurie plot

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



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

Mainz & Troitsk

[Weinheimer, hep-ex/0210050]

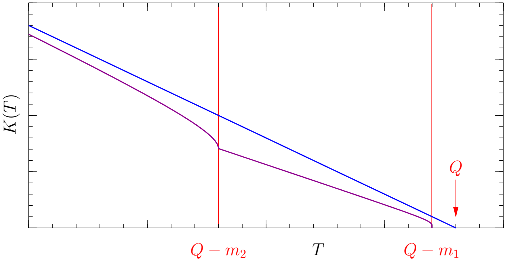
future: KATRIN

[www.katrin.kit.edu]

start data taking in 2015

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

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 ($m_k \ll Q - T$)

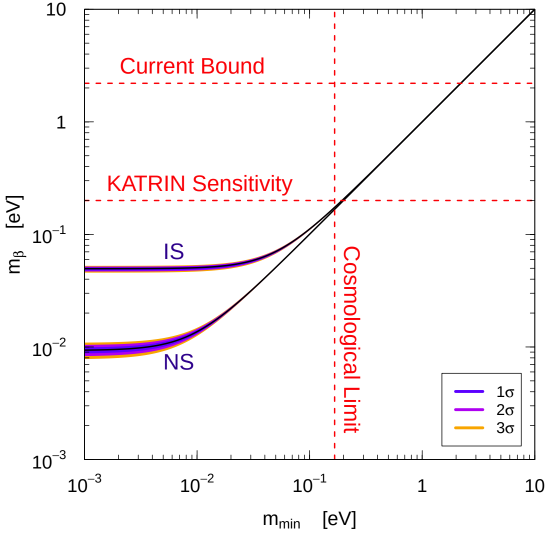
effective mass: $$\boxed{m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2}$$

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

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

Predictions of 3ν-Mixing Paradigm

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

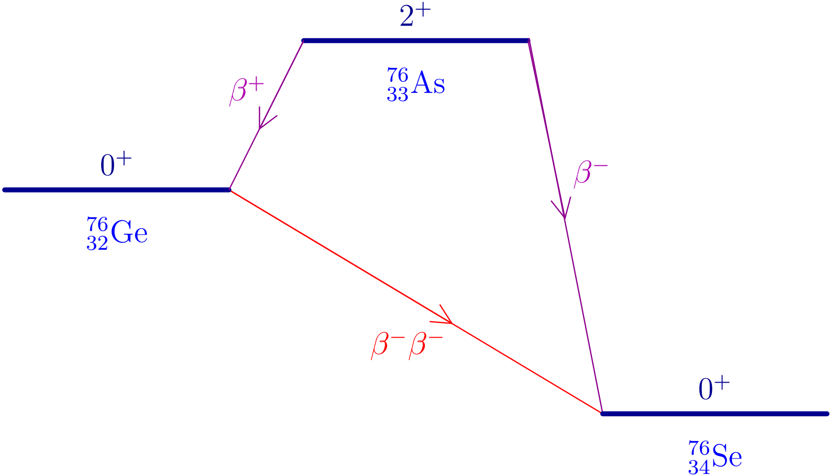


- **Quasi-Degenerate:**
  $m_\beta^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2$
- **Inverted Hierarchy:**
  $m_\beta^2 \simeq (1 - s_{13}^2)\Delta m_{\rm A}^2 \simeq \Delta m_{\rm A}^2$
- **Normal Hierarchy:**
  $m_\beta^2 \simeq s_{12}^2 c_{13}^2 \Delta m_{\rm S}^2 + s_{13}^2 \Delta m_{\rm A}^2$
  $\simeq 2 \times 10^{-5} + 6 \times 10^{-5} \, {\rm eV}^2$
- $m_\beta \lesssim 4 \times 10^{-2} \, {\rm eV}$

$\Downarrow$

Normal Spectrum

Neutrinoless Double-Beta Decay



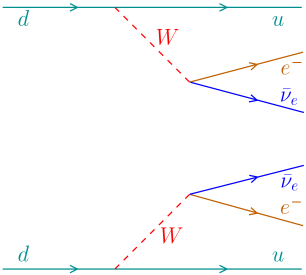
Effective Majorana Neutrino Mass: $$m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$$

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

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

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

second order weak interaction process
in the Standard Model

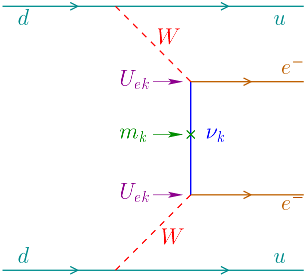


Neutrinoless Double-β Decay: $\Delta L = 2$

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

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

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

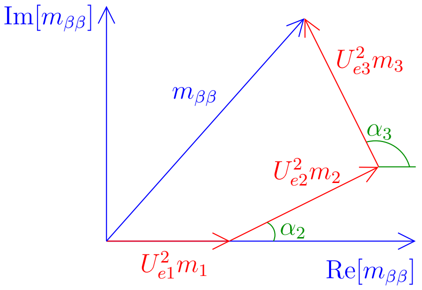


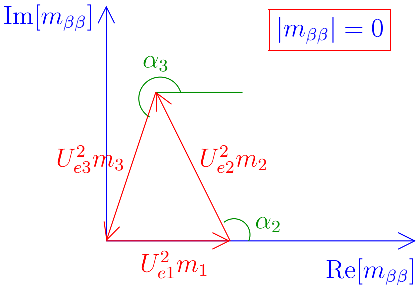
Effective Majorana Neutrino Mass

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

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

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





Experimental Bounds

KamLAND-Zen (^{136}Xe) [arXiv:1211.3863]

$T^{0\nu}_{1/2} > 1.9 \times 10^{25}\,\text{y}\,(90\%\ \text{C.L.}) \Longrightarrow |m_{\beta\beta}| \lesssim 0.12 - 0.25\,\text{eV}$ (KLZ+EXO)

EXO (^{136}Xe) [PRL 109 (2012) 032505]

$T^{0\nu}_{1/2} > 1.6 \times 10^{25}\,\text{y}\,(90\%\ \text{C.L.}) \Longrightarrow |m_{\beta\beta}| \lesssim 0.14 - 0.38\,\text{eV}$

CUORICINO (^{130}Te) [AP 34 (2011) 822]

$T^{0\nu}_{1/2} > 2.8 \times 10^{24}\,\text{y}\,(90\%\ \text{C.L.}) \Longrightarrow |m_{\beta\beta}| \lesssim 0.3 - 0.7\,\text{eV}$

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

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

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

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

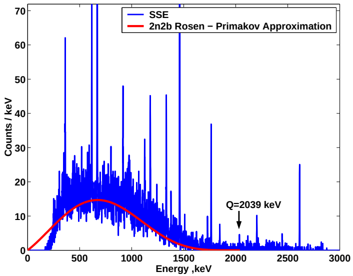
NEMO 3 (^{100}Mo) [PRL 95 (2005) 182302]

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

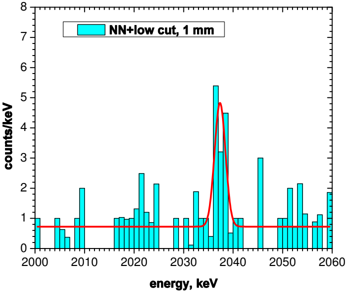
Experimental Positive Indication

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

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



[PLB 586 (2004) 198]

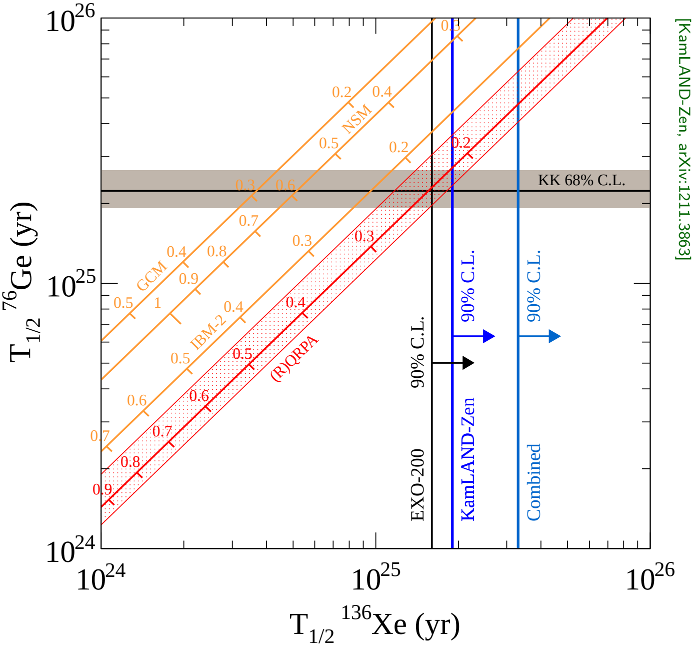


[MPLA 21 (2006) 1547]

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

very exciting: Majorana ν and large mass scale

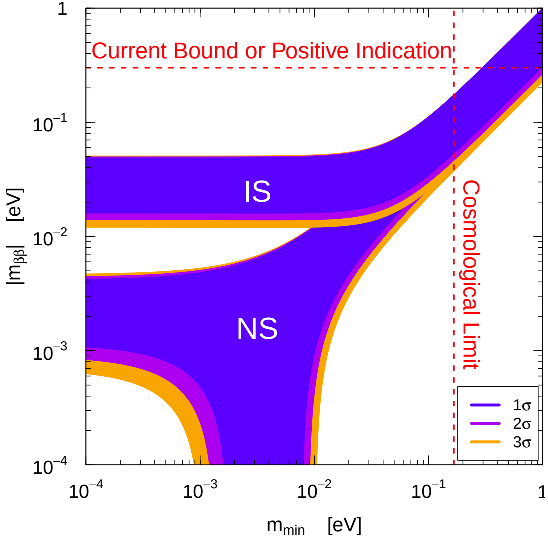
partially excluded by KamLAND-Zen, EXO and CUORICINO



10^{26}
10^{25}
10^{24}
$T_{1/2}$ ^{76}Ge (yr)
$T_{1/2}$ ^{136}Xe (yr)
GCM
NSM
IBM-2
(R)QRPA
KK 68% C.L.
90% C.L.
EXO-200
KamLAND-Zen
Combined
[KamLAND-Zen, arXiv:1211.3863]

Predictions of 3ν-Mixing Paradigm

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

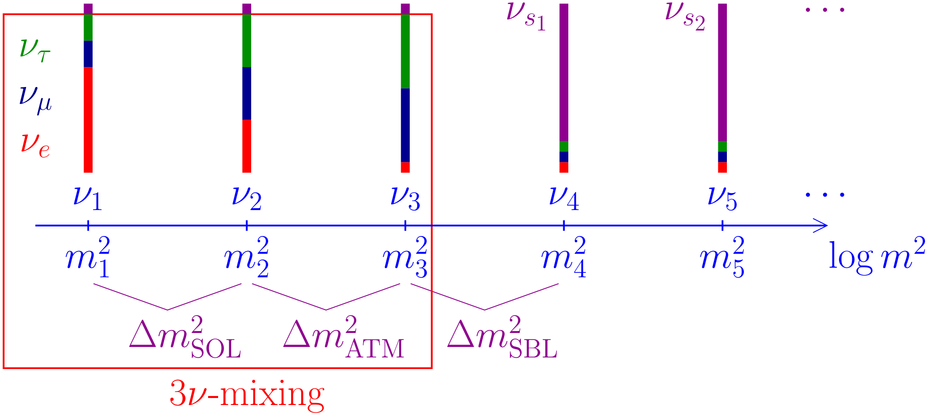


- Positive indication: tension with cosmology
- Quasi-Degenerate:
  $$|m_{\beta\beta}| \simeq m_\nu \sqrt{1 - s^2_{2\vartheta_{12}} s^2_{\alpha_2}}$$
- Inverted Hierarchy:
  $$|m_{\beta\beta}| \simeq \sqrt{\Delta m^2_{\text{A}} (1 - s^2_{2\vartheta_{12}} s^2_{\alpha_2})}$$
- Normal Hierarchy:
  $$|m_{\beta\beta}| \simeq |s^2_{12} \sqrt{\Delta m^2_{\text{S}}} + e^{i\alpha} s^2_{13} \sqrt{\Delta m^2_{\text{A}}}|$$
  $$\simeq |2.7 + 1.2 e^{i\alpha}| \times 10^{-3} \, \text{eV}$$

$m_1 \gtrsim 10^{-3}$ eV $\Rightarrow$ cancellation?

$|m_{\beta\beta}| \lesssim 10^{-2}$ eV $\Longrightarrow$ Normal Spectrum

Beyond Three-Neutrino Mixing



Sterile Neutrinos from Physics Beyond the SM

- Neutrinos are special in the Standard Model: the only neutral fermions
- In extensions of SM neutrinos can mix with non-SM fermions
- SM: $L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$ $\qquad \widetilde{\Phi} = i\sigma_2 \, \Phi^* = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \xrightarrow[\text{Breaking}]{\text{Symmetry}} \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$
- SM singlet $\overline{L_L}\widetilde{\Phi}$ can couple to new singlet chiral fermion field f_R related to physics beyond the SM $[Y(\overline{L_L}) = +1, \ Y(\widetilde{\Phi}) = -1]$
- Known examples: light ν_R from see-saw, SUSY (ν_R, axino, ...), extra dimensions (Kaluza-Klein modes), mirror world, ...
- Dirac mass term $\sim \overline{L_L}\widetilde{\Phi} f_R \quad + \quad$ Majorana mass term $\sim \overline{f_R^c} f_R$
- f_R is often called Right-Handed Neutrino: $f_R \to \nu_R$

Light Sterile Neutrinos

- Light anti-ν_R are called sterile neutrinos

$$\nu_R^c \to \nu_{sL} \qquad \text{(left-handed)}$$

- Sterile means no standard model interactions
- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into light sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + 3ν-mixing:

$$\begin{array}{ccccc} & \Delta m^2_{21} \ll |\Delta m^2_{31}| \ll |\Delta m^2_{41}| \leq \ldots & & & \\ \nu_1 & \nu_2 & \nu_3 & \nu_4 & \ldots \\ \nu_e & \nu_\mu & \nu_\tau & \nu_{s_1} & \ldots \end{array}$$

- In this talk I consider sterile neutrinos with mass scale $\sim 1\,\mathrm{eV}$ in light of short-baseline LSND, MiniBooNE, Reactor Anomaly, Gallium Anomaly.

- Other possibilities (not incompatible):

  - Very light sterile neutrinos with mass scale $\ll 1\,\mathrm{eV}$: important for solar neutrino phenomenology

    [Das, Pulido, Picariello, PRD 79 (2009) 073010]

    [de Holanda, Smirnov, PRD 83 (2011) 113011]

  - Heavy sterile neutrinos with mass scale $\gg 1\,\mathrm{eV}$: could be Warm Dark Matter

    [Kusenko, Phys. Rept. 481 (2009) 1]

    [Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191]

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

No CP Violation!

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

Perturbation of 3ν Mixing

$$|U_{e4}|^2 \ll 1\,, \quad |U_{\mu 4}|^2 \ll 1\,, \quad |U_{\tau 4}|^2 \ll 1\,, \quad |U_{s4}|^2 \simeq 1$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

$$\sin^2 2\vartheta_{\alpha\alpha} \ll 1$$

$$\Downarrow$$

$$|U_{\alpha 4}|^2 \simeq \frac{\sin^2 2\vartheta_{\alpha\alpha}}{4}$$

Effective SBL Oscillation Probabilities in 3+2 Schemes

$$\phi_{kj} = \Delta m^2_{kj} L / 4E$$

$$\eta = \arg[U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*]$$

$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2\phi_{51} + 8|U_{\mu 4} U_{e4} U_{\mu 5} U_{e5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} \overset{(+)}{-} \eta)$$

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2\phi_{41} + |U_{\alpha 5}|^2 \sin^2\phi_{51}) - 4|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2\phi_{54}$$

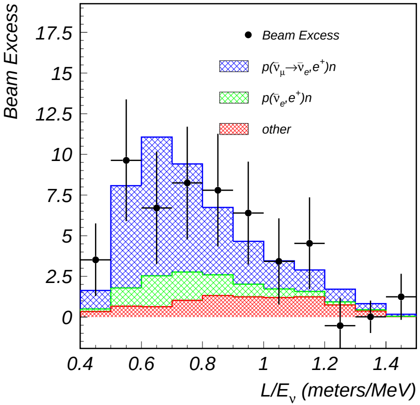
[Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004; Maltoni, Schwetz, PRD 76 (2007) 093005; Karagiorgi et al, PRD 80 (2009) 073001; Kopp, Maltoni, Schwetz, PRL 107 (2011) 091801; Giunti, Laveder, PRD 84 (2011) 073008; Donini et al, arXiv:1205.5230; Conrad, Ignarra, Karagiorgi, Shaevitz, Spitz, arXiv:1207.4765]

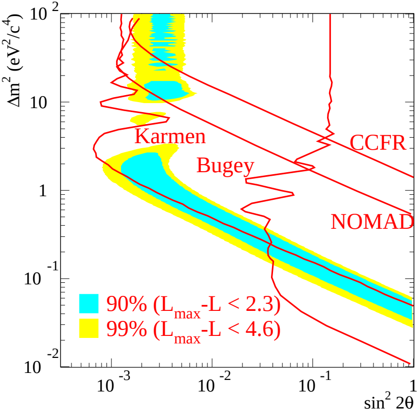
- More parameters: 7 (vs 3 in 3+1)
- CP violation
- Why not 3+3?

LSND

[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 30\,\mathrm{m}$ $\quad 20\,\mathrm{MeV} \leq E \leq 200\,\mathrm{MeV}$



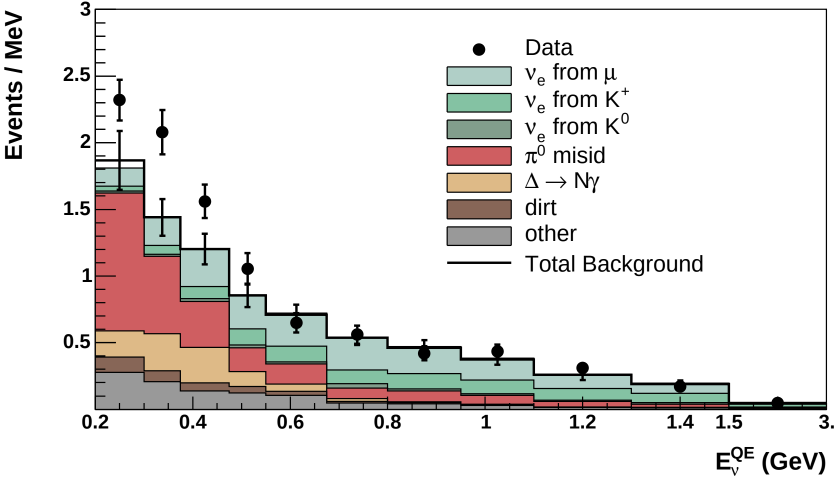


3.8σ excess $\quad \Delta m^2_{\mathrm{LSND}} \gtrsim 0.2\,\mathrm{eV}^2 \quad (\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

MiniBooNE Neutrinos

[PRL 98 (2007) 231801; PRL 102 (2009) 101802]

$\nu_\mu \to \nu_e$ $\quad L \simeq 541\,\text{m}$ $\quad 200\,\text{MeV} \le E \lesssim 3\,\text{GeV}$

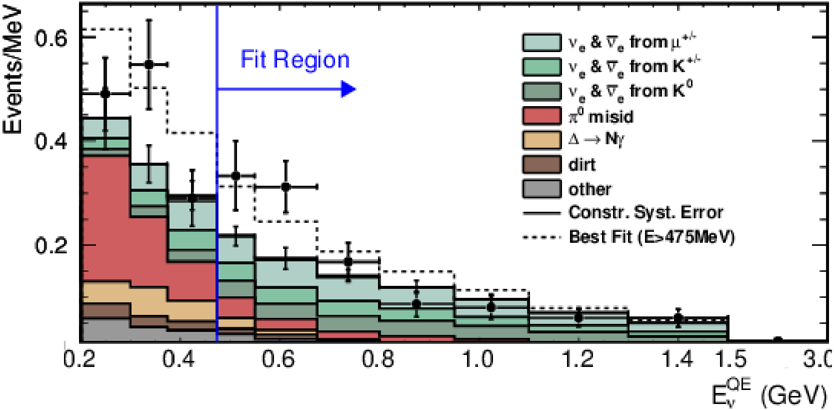


- no $\nu_\mu \to \nu_e$ signal corresponding to LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal $(E > 475\,\text{MeV})$
- low-energy anomaly

MiniBooNE Antineutrinos - 2009-2010

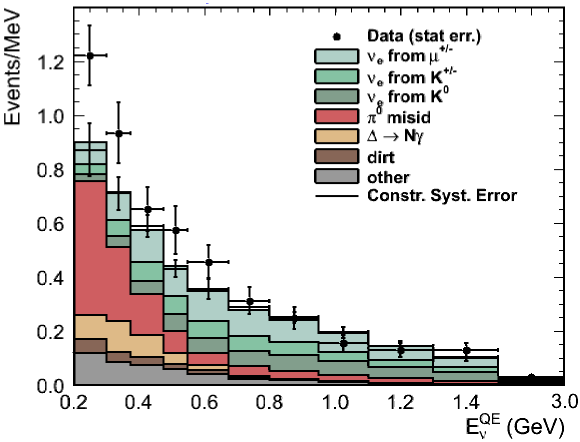
[PRL 103 (2009) 111801; PRL 105 (2010) 181801]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 541\,\text{m}$ $\quad 200\,\text{MeV} \le E \lesssim 3\,\text{GeV}$



- agreement with LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal ($E > 475\,\text{MeV}$)
- similar L/E but different L and E $\Longrightarrow$ oscillations
- CP violation?

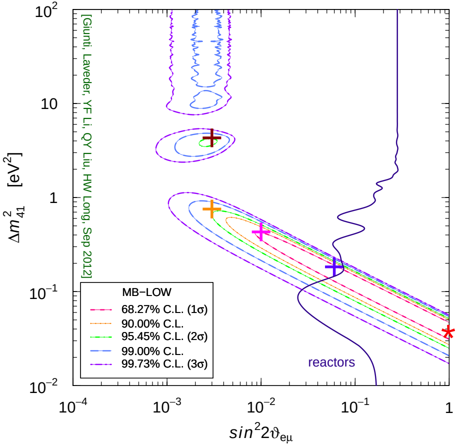
MiniBooNE $\bar{\nu}$ - Neutrino 2012 - 6 June

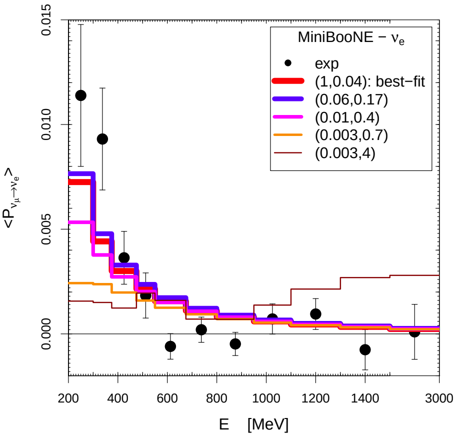


		1st half			2nd half	
	data	mc	excess	data	mc	excess
200-475	119	100.5±14.3	18.5 (1.3s)	138	100.0±14.1	38 (2.7s)
475-1250	120	99.1±14.0	20.9 (1.5s)	101	103.1±14.4	-2.2 (-0.2s)

? agreement with LSND signal ? CP violation ?

MiniBooNE ν and $\bar{\nu}$ - arXiv:1207.4809





- Fit of low-energy excess is marginal
- It requires $\Delta m^2_{41} \lesssim 0.4 \mathrm{eV}^2$
- Neutrino energy reconstruction problem?

[Martini, Ericson, Chanfray, arXiv:1202.4745]

Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006]

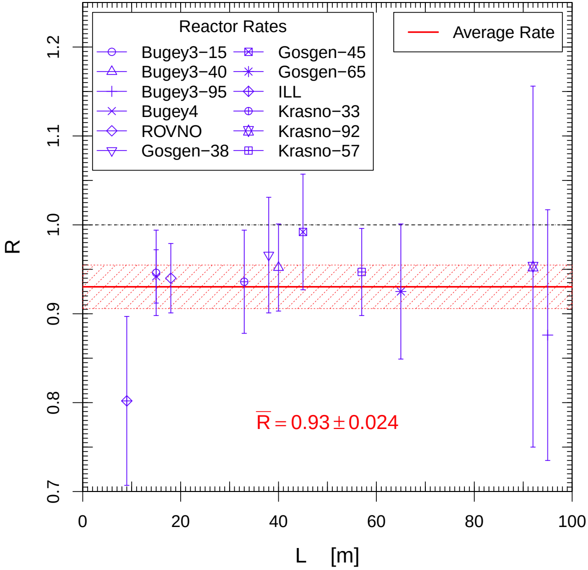
[update in White Paper, arXiv:1204.5379

new reactor $\bar{\nu}_e$ fluxes

[Mueller et al, PRC 83 (2011) 054615]

[Huber, PRC 84 (2011) 024617]

2.8σ anomaly



Gallium Anomaly

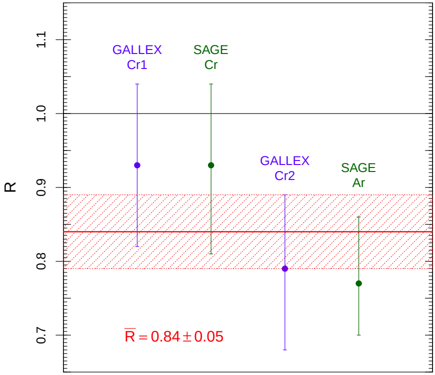
Gallium Radioactive Source Experiments: GALLEX and SAGE

Detection Process: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

Anomaly supported by new ${}^{71}\text{Ga}({}^{3}\text{He}, {}^{3}\text{H}){}^{71}\text{Ge}$ cross section measurement

[Frekers et al., PLB 706 (2011) 134]



$E \sim 0.7\,\text{MeV}$

$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m}$

$\langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$

2.9σ anomaly

3+1 SBL ν_e and $\bar{\nu}_e$ Survival Probability

$$P_{\overset{(-)}{\nu_e} \to \overset{(-)}{\nu_e}} = 1 - \sin^2 2\vartheta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$$

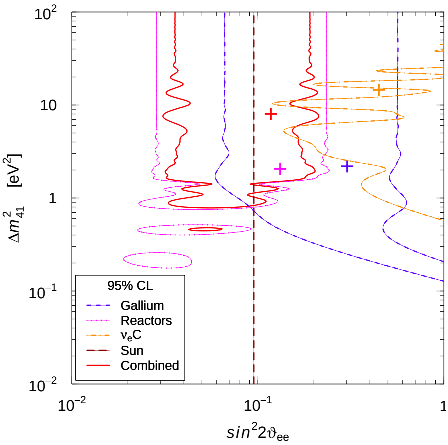
standard parameterization

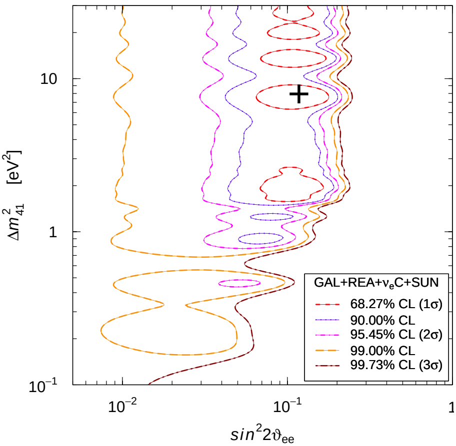
$$U_{e1} = c_{12} c_{13} c_{14} \quad U_{e2} = s_{12} c_{13} c_{14} \quad U_{e3} = s_{13} c_{14} e^{-i\delta_{13}} \quad U_{e4} = s_{14} e^{-i\delta_{14}}$$

$$\sin^2 2\vartheta_{ee} = \sin^2 2\vartheta_{14}$$

Global ν_e and $\bar{\nu}_e$ Disappearance

[Giunti, Laveder, Y.F. Li, Q.Y. Liu, H.W. Long, PRD 86 (2012) 113014]





$\nu_e + {}^{12}\text{C} \to {}^{12}\text{N}_{\text{g.s.}} + e^-$

KARMEN + LSND

[Conrad, Shaevitz, PRD 85 (2012) 013017]

[Giunti, Laveder, PLB 706 (2011) 200]

solar ν_e + KamLAND $\bar{\nu}_e$ + ϑ_{13}

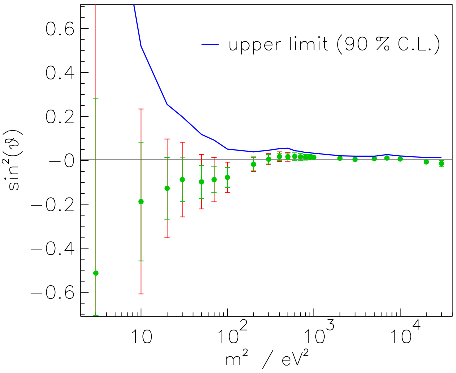
[Giunti, Li, PRD 80 (2009) 113007]

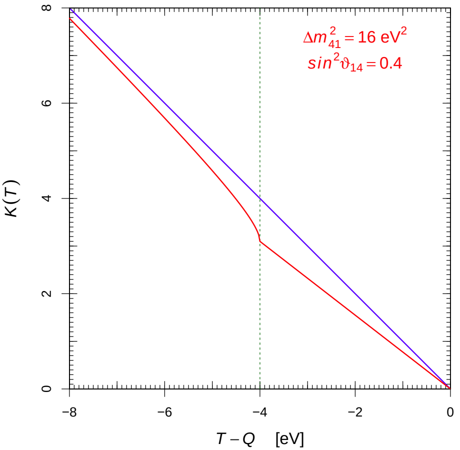
[Palazzo, PRD 83 (2011) 113013]

[Palazzo, PRD 85 (2012) 077301]

Mainz Limit on m_4^2

[Kraus, Singer, Valerius, Weinheimer, arXiv:1210.4194]

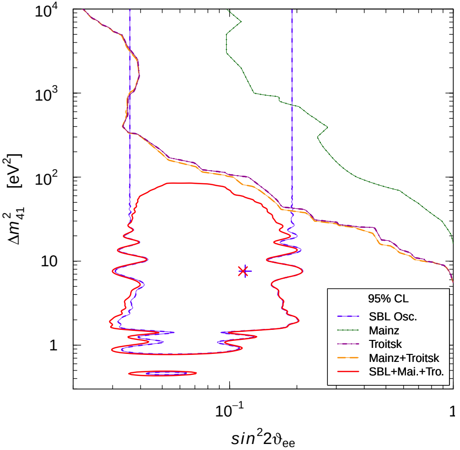


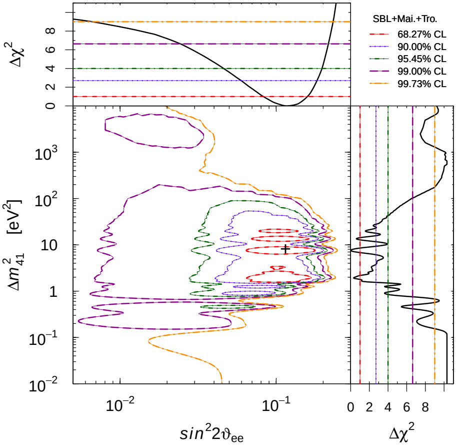


$$m_4 \gg m_1, m_2, m_3 \implies \Delta m^2_{41} \equiv m_4^2 - m_1^2 \simeq m_4^2$$

Troitsk: Surprising Much Better Limit on m_4^2

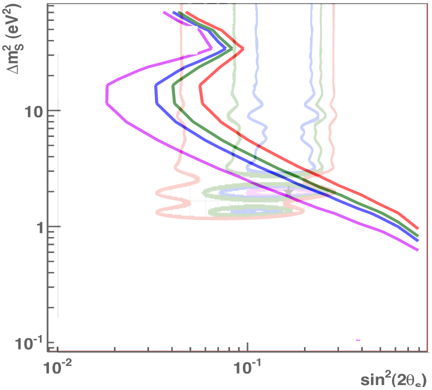
[Belesev, Berlev, Geraskin, Golubev, Likhovid, Nozik, Pantuev, Parfenov, Skasyrskaya, arXiv:1211.7193]



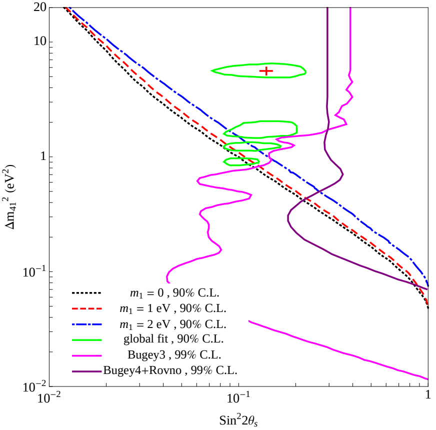


[Giunti, Laveder, Y.F. Li, H.W. Long, PRD 87 (2013) 013004]

KATRIN Sensitivity



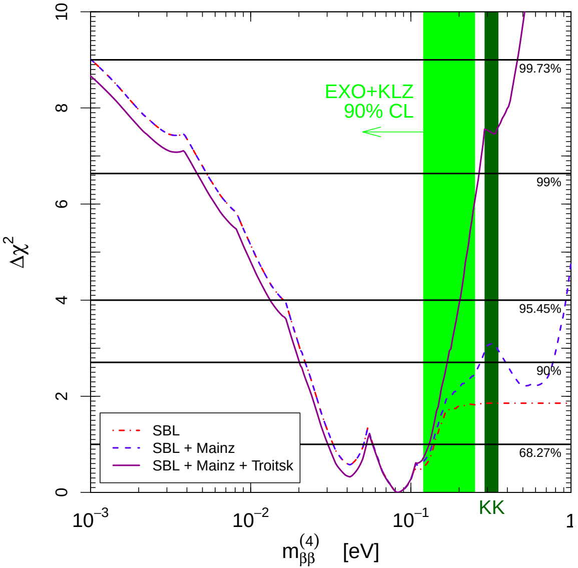
[Formaggio, Barrett, PLB 706 (2011) 68]



[Esmaili, Peres, PRD 85 (2012) 117301]

[see also Sejersen Riis, Hannestad, JCAP (2011) 1475; Sejersen Riis, Hannestad, Weinheimer, PRC 84 (2011) 045503]

Neutrinoless Double-β Decay



$$|m_{\beta\beta}| = \left|\sum_{k=1}^{4} U_{ek}^2 \, m_k\right|$$

$$m_{\beta\beta}^{(4)} = |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

caveat:

possible cancellation with $m_{\beta\beta}^{(3\nu-IH)}$

[Barry et al, JHEP 07 (2011) 091]

[Li, Liu, PLB 706 (2012) 406]

[Rodejohann, arXiv:1206.2560]

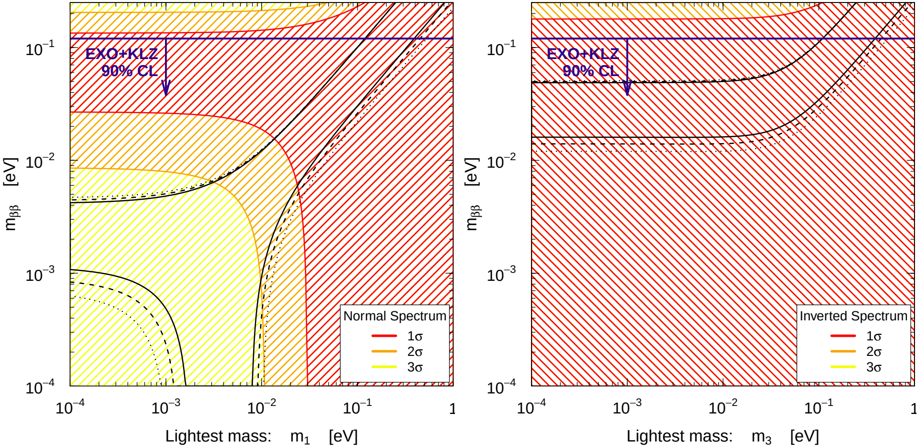
Cancellation with $m_{\beta\beta}^{(\text{light})}$?

[Barry, Rodejohann, Zhang, JHEP 07 (2011) 091]; Li, Liu, PLB 706 (2012) 406; Rodejohann, arXiv:1206.2560]

$$m_{\beta\beta}^{(\text{light})} = \left| \sum_{k=1}^{3} U_{ek}^2 \, m_k \right| \qquad m_{\beta\beta}^{(4)} = |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

$$m_{\beta\beta} = m_{\beta\beta}^{(\text{light})} + e^{i\alpha_4} m_{\beta\beta}^{(4)} \qquad m_{\beta\beta}^{(4)} \gtrsim 10^{-2}\,\text{eV}$$

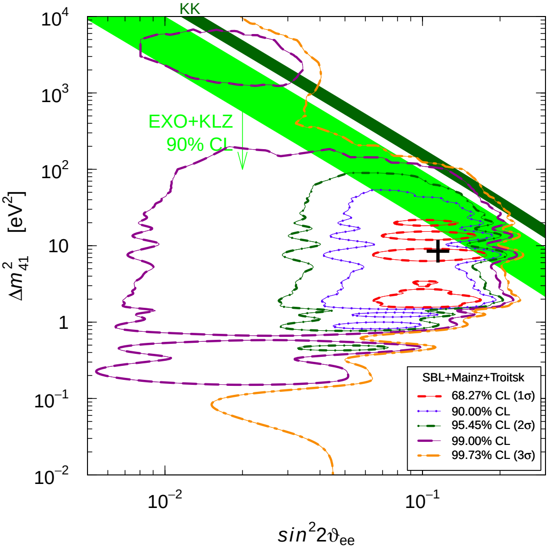
- **Normal Hierarchy:** $m_{\beta\beta}^{(\text{light})} \lesssim 4.5 \times 10^{-3}\,\text{eV}$ (95% CL)
  no cancellation is possible
- **Inverted Hierarchy:** $1.4 \times 10^{-2} \lesssim m_{\beta\beta}^{(\text{light})} \lesssim 5.0 \times 10^{-2}\,\text{eV}$ (95% CL)
  cancellation is possible
- **Quasi-Degenerate:** $m_{\beta\beta}^{(\text{light})} \gtrsim 5.0 \times 10^{-2}\,\text{eV}$ cancellation is possible


EXO+KLZ
90% CL
Normal Spectrum
1σ
2σ
3σ
$m_{\beta\beta}$ [eV]
Lightest mass: m_1 [eV]
EXO+KLZ
90% CL
Inverted Spectrum
1σ
2σ
3σ
$m_{\beta\beta}$ [eV]
Lightest mass: m_3 [eV]

Assumption: no cancellation

$$m_{\beta\beta} \geq m_{\beta\beta}^{(4)} = |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

$$\Delta m_{41}^2 = \left(\frac{m_{\beta\beta}^{(4)}}{|U_{e4}|^2} \right)^2 \leq \left(\frac{m_{\beta\beta}}{|U_{e4}|^2} \right)^2$$



3+1: Appearance vs Disappearance

- ν_e disappearance experiments:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

- ν_μ disappearance experiments:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 \left(1 - |U_{\mu4}|^2\right) \simeq 4|U_{\mu4}|^2$$

- $\nu_\mu \to \nu_e$ experiments:

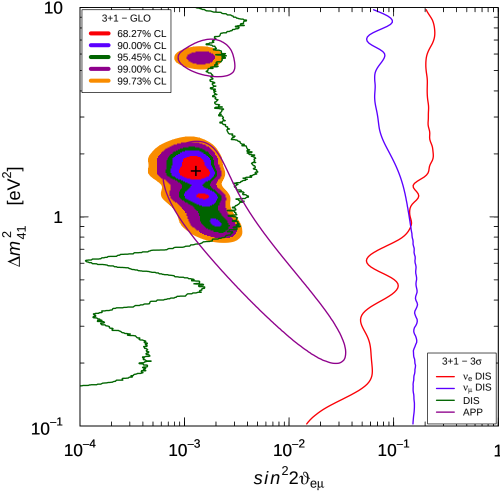
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ $\Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[Okada, Yasuda, Int. J. Mod. Phys. A12 (1997) 3669-3694]

[Bilenky, Giunti, Grimus, Eur. Phys. J. C1 (1998) 247]

3+1 Global Fit



No Osc. GoF = 1.3%

3+1 GoF = 32%

PGoF = 4%

- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND (Y), MiniBooNE (?), ICARUS (N), KARMEN (N), NOMAD (N)
- DIS ν_e & $\bar{\nu}_e$: Reactors (Y), Gallium (Y), $\nu_e C$ (N), Solar (N)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW (N), MINOS (N), Atmospheric (N), MiniBooNE/SciBooNE (N)

Cosmology

- N_s = number of thermalized sterile neutrinos (not necessarily integer)

- CMB+LSS in ΛCDM: $N_s = 1.3 \pm 0.9$ $\quad m_s < 0.66\,\text{eV}$ (95% C.L.)

[Hamann, Hannestad, Raffelt, Tamborra, Wong, PRL 105 (2010) 181301]

$$N_s = 1.61 \pm 0.92 \qquad m_s < 0.70\,\text{eV} \quad (95\%\ \text{C.L.})$$

[Giusarma, Corsi, Archidiacono, de Putter, Melchiorri, Mena, Pandolfi, PRD 83 (2011) 115023]

- BBN: $\begin{cases} N_s \leq 1 \text{ at } 95\% \text{ C.L.} \\ N_s = 0.0 \pm 0.5 \end{cases}$

[Mangano, Serpico, PLB 701 (2011) 296]

[Pettini, Cooke, arXiv:1205.3785]

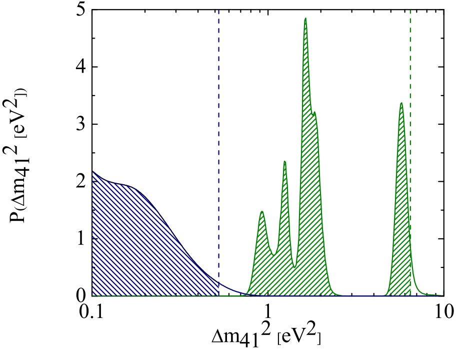
- CMB+LSS+BBN in ΛCDM: $N_s = 0.85^{+0.39}_{-0.56}$ (95% C.L.)

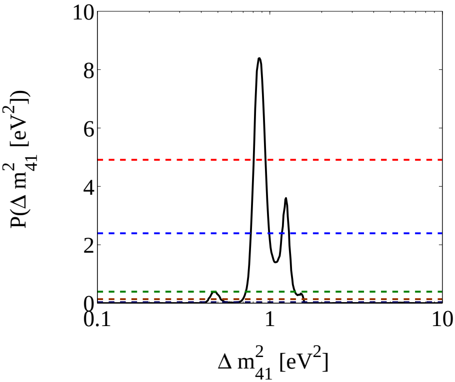
[Hamann, Hannestad, Raffelt, Wong, JCAP 1109 (2011) 034]

- Standard ΛCDM: 3+1 allowed, 3+2 disfavored

Combined Oscillation and Cosmology Fit

[Archidiacono, Fornengo, Giunti, Melchiorri, PRD 86 (2012) 065028]





- Mass Hierarchy: $m_4 \gg m_3, m_2, m_1$ $\Longrightarrow$ $m_4 \simeq \sqrt{\Delta m^2_{41}}$
- Cosmology: $m_4 < 0.73\,\text{eV}^2$ (95% Bayesian CL)
- Oscillation + Cosmology: $0.85 < m_4 < 1.18\,\text{eV}^2$ (95% Bayesian CL)

Conclusions

- Robust Three-Neutrino Mixing Paradigm. Open problems: $\vartheta_{23} < 45°$?, CP Violation, Mass Hierarchy, Absolute Mass Scale, Dirac or Majorana?
- Short-Baseline ν_e and $\bar{\nu}_e$ 3+1 Disappearance:
  - Reactor $\bar{\nu}_e$ anomaly is alive and exciting
  - Gallium ν_e anomaly strengthened by new cross-section measurements
  - Many promising projects to test short-baseline ν_e and $\bar{\nu}_e$ disappearance in a few years with reactors and radioactive sources
  - Independent tests through effect of m_4 in β-decay and $(\beta\beta)_{0\nu}$-decay
- Short-Baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ LSND Signal:
  - MiniBooNE experiment has been inconclusive
  - Better experiments are needed to check LSND signal
  - If LSND signal is confirmed $m_4 \sim 1\,\text{eV}$, marginally compatible with ΛCDM
- Light Sterile Neutrinos:
  - First new particle beyond the Standard Model?
  - Strongest hint from Reactor and Gallium Anomalies will be checked in several near-future source and reactor experiments
  - Maybe LSND observed a fluctuation of small $\bar{\nu}_\mu \to \bar{\nu}_e$ transition probability that can be observed in ICARUS@CERN
  - I have great hopes in near-future experiments!