

Open Questions in Neutrino Physics

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CNRS - Campus Gérard Mégie

27 June 2013

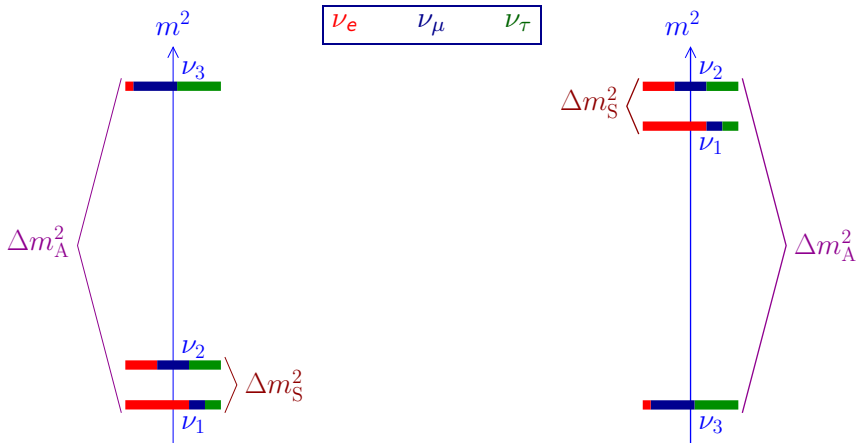
Experimental Evidences of Neutrino Oscillations

<p>Solar $\nu_e \rightarrow \nu_\mu, \nu_\tau$</p> <p>VLBL Reactor $\bar{\nu}_e$ disappearance</p>	$\left(\begin{array}{c} \text{SNO, BOREXino} \\ \text{Super-Kamiokande} \\ \text{GALLEX/GNO, SAGE} \\ \text{Homestake, Kamiokande} \\ \\ \text{(KamLAND)} \end{array} \right)$	$\rightarrow \left\{ \begin{array}{l} \Delta m_S^2 \simeq 7.6 \times 10^{-5} \text{ eV}^2 \\ \sin^2 \vartheta_S \simeq 0.30 \end{array} \right.$
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<p>Atmospheric $\nu_\mu \rightarrow \nu_\tau$</p> <p>LBL Accelerator ν_μ disappearance</p> <p>LBL Accelerator $\nu_\mu \rightarrow \nu_\tau$</p>	$\left(\begin{array}{c} \text{Super-Kamiokande} \\ \text{Kamiokande, IMB} \\ \text{MACRO, Soudan-2} \\ \\ \text{(K2K, MINOS, T2K)} \\ \\ \text{(Opera)} \end{array} \right)$	$\rightarrow \left\{ \begin{array}{l} \Delta m_A^2 \simeq 2.4 \times 10^{-3} \text{ eV}^2 \\ \sin^2 \vartheta_A \simeq 0.50 \end{array} \right.$
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<p>LBL Accelerator $\nu_\mu \rightarrow \nu_e$</p> <p>LBL Reactor $\bar{\nu}_e$ disappearance</p>	$\left(\begin{array}{c} \text{(T2K, MINOS)} \\ \\ \text{(Daya Bay, RENO)} \\ \text{Double Chooz} \end{array} \right)$	$\rightarrow \left\{ \begin{array}{l} \Delta m_A^2 \\ \sin^2 \vartheta_{13} \simeq 0.023 \end{array} \right.$
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Three-Neutrino Mixing Paradigm



Normal Spectrum

$$\Delta m_S^2 = \Delta m_{21}^2 = 7.50 \pm 0.20 \times 10^{-5} \text{ eV}^2$$

uncertainty $\simeq 2.6\%$

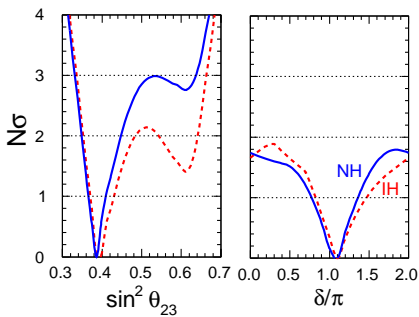
$$\Delta m_A^2 = |\Delta m_{31}^2| \simeq |\Delta m_{32}^2| = 2.32_{-0.08}^{+0.12} \times 10^{-3} \text{ eV}^2 \quad \text{uncertainty} \simeq 5\%$$

$$\begin{aligned}
 U &= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix} \\
 &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix} \\
 &\quad \vartheta_{23} = \vartheta_A \qquad \text{Chooz, Palo Verde} \qquad \vartheta_{12} = \vartheta_S \qquad \beta\beta_{0\nu} \\
 &\quad \sin^2 \vartheta_{23} \simeq 0.4 - 0.6 \qquad \text{T2K, MINOS} \qquad \sin^2 \vartheta_{12} = 0.30 \pm 0.01 \\
 &\quad \text{Daya Bay, RENO} \\
 &\quad \sin^2 \vartheta_{13} = 0.023 \pm 0.002
 \end{aligned}$$

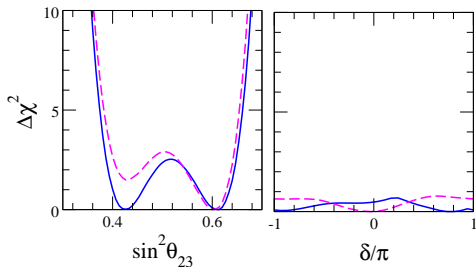
$$\frac{\delta \sin^2 \vartheta_{23}}{\sin^2 \vartheta_{23}} \simeq 40\%$$

$$\frac{\delta \sin^2 \vartheta_{13}}{\sin^2 \vartheta_{13}} \simeq 10\%$$

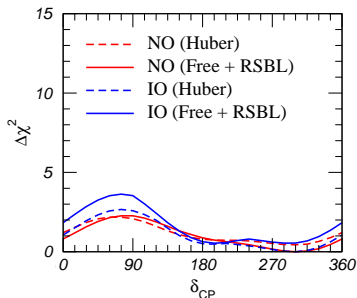
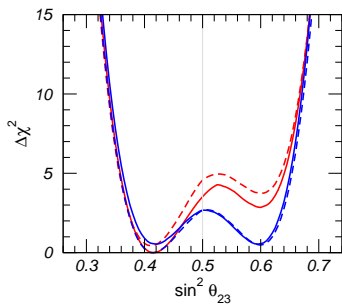
$$\frac{\delta \sin^2 \vartheta_{12}}{\sin^2 \vartheta_{12}} \simeq 5\%$$



[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 ν , T2K, NO ν A,
- ▶ Mass Hierarchy ?
 - ▶ NO ν A, Atmospheric ν , Day Bay II, RENO-50, Supernova ν , ...
- ▶ CP violation ?
 - ▶ NO ν A, LAGUNA-LBNO, LBNE (USA), HyperK, ...
- ▶ Absolute Mass Scale ?
 - ▶ β Decay, Neutrinoless Double- β Decay, Cosmology, ...
- ▶ Dirac or Majorana ?
 - ▶ Neutrinoless Double- β Decay, ...
- ▶ Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

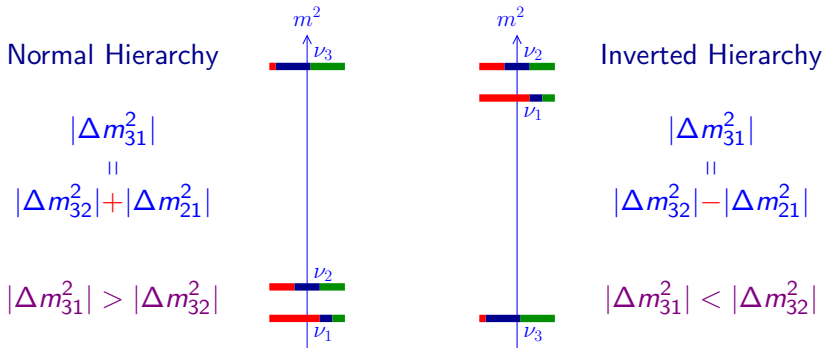
Mass Hierarchy

1. Matter Effect (Atmospheric, Long-Baseline, Supernova Experiments):

▶ $\nu_e \leftrightarrow \nu_\mu$ MSW resonance: $V = \frac{\Delta m_{13}^2 \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m_{13}^2 > 0 \quad \text{NH}$

▶ $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ MSW resonance: $V = -\frac{\Delta m_{13}^2 \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m_{13}^2 < 0 \quad \text{IH}$

2. Phase Difference (Reactor $\bar{\nu}_e \rightarrow \bar{\nu}_e$):



CP Violation

$$P_{\nu_\alpha \rightarrow \nu_\beta} - P_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta} = -16 J_{\alpha\beta} \sin\left(\frac{\Delta m_{21}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

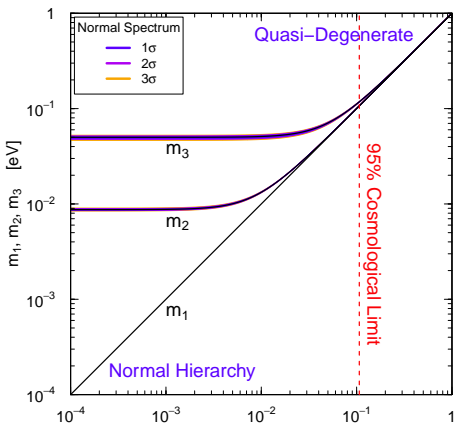
$$J_{\alpha\beta} = \text{Im}(U_{\alpha 1} U_{\alpha 2}^* U_{\beta 1}^* U_{\beta 2}) = \pm J$$

$$J = s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2 \sin \delta_{13}$$

Necessary conditions for observation of CP violation:

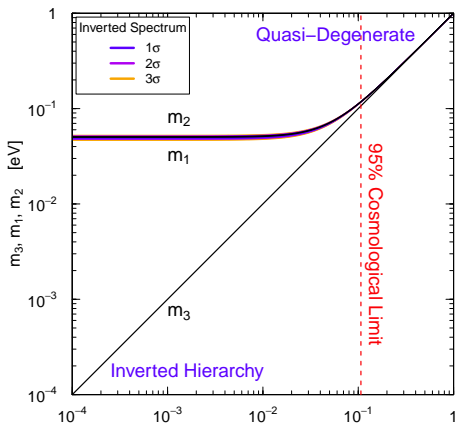
- ▶ Sensitivity to all mixing angles, including small ϑ_{13}
- ▶ Sensitivity to oscillations due to Δm_{21}^2 and Δm_{31}^2

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

95% Cosmological Limit: Planck + WMAP9 + highL + BAO [\[arXiv:1303.5076\]](https://arxiv.org/abs/1303.5076)

Tritium Beta-Decay

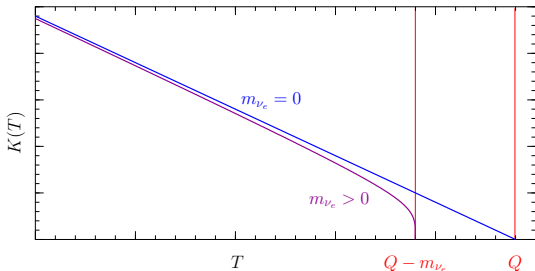


$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E) p E (Q - T) \sqrt{(Q - T)^2 - m_{\nu_e}^2}$$

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

Kurie plot

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



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

Mainz & Troitsk

[Weinheimer, hep-ex/0210050]

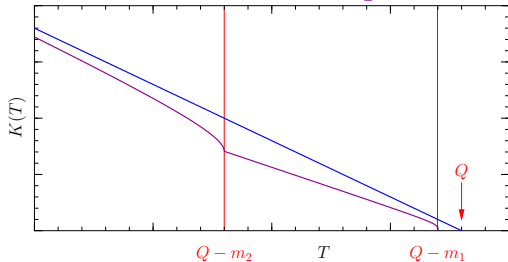
future: KATRIN

[www.katrin.kit.edu]

start data taking in 2015

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

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



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 ($m_k \ll Q - T$)

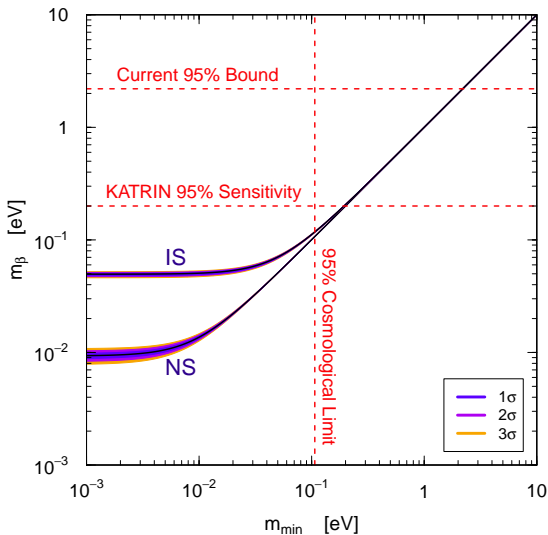
effective mass:

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

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

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:

$$m_\beta^2 \simeq (1 - s_{13}^2) \Delta m_A^2 \simeq \Delta m_A^2$$

- ▶ Normal Hierarchy:

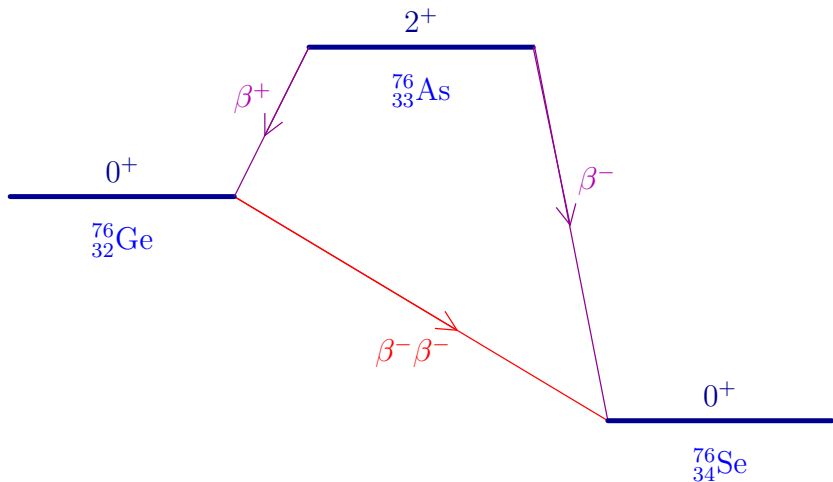
$$\begin{aligned} m_\beta^2 &\simeq s_{12}^2 c_{13}^2 \Delta m_S^2 + s_{13}^2 \Delta m_A^2 \\ &\simeq 2 \times 10^{-5} + 6 \times 10^{-5} \text{ eV}^2 \end{aligned}$$

- ▶ $m_\beta \lesssim 4 \times 10^{-2} \text{ eV}$



Normal Spectrum

Neutrinoless Double-Beta Decay



Effective Majorana Neutrino Mass:

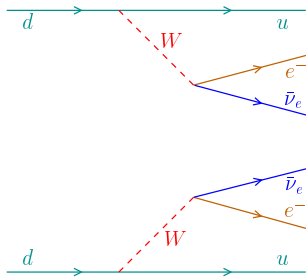
$$m_{\beta\beta} = \sum_k U_{ek}^2 m_k$$

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

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

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

second order weak interaction process
in the Standard Model



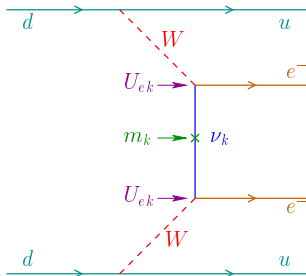
Neutrinoless Double- β Decay: $\Delta L = 2$

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

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

effective
Majorana
mass

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

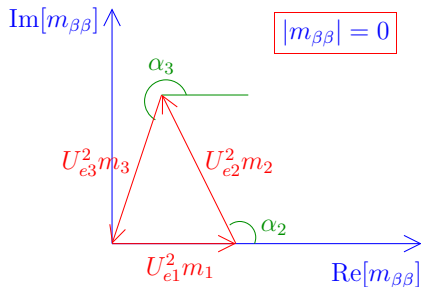
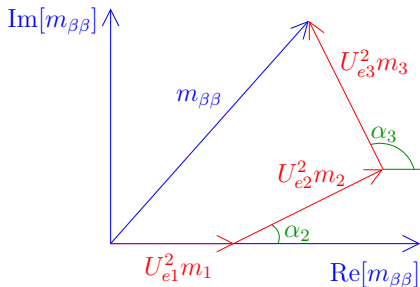


Effective Majorana Neutrino Mass

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

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

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



Experimental Bounds

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

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

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

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

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

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

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

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

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

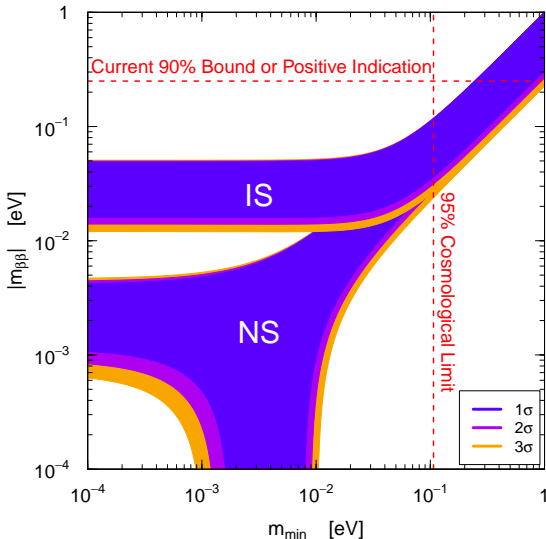
$$T_{1/2}^{0\nu} > 1.57 \times 10^{25} \text{ y (90\% C.L.)} \implies |m_{\beta\beta}| \lesssim 0.33 - 1.35 \text{ eV}$$

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

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

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:

$$|m_{\beta\beta}| \simeq m_\nu \sqrt{1 - s_{2\vartheta_{12}}^2 s_{\alpha_2}^2}$$

▶ Inverted Hierarchy:

$$|m_{\beta\beta}| \simeq \sqrt{\Delta m_A^2 (1 - s_{2\vartheta_{12}}^2 s_{\alpha_2}^2)}$$

▶ Normal Hierarchy:

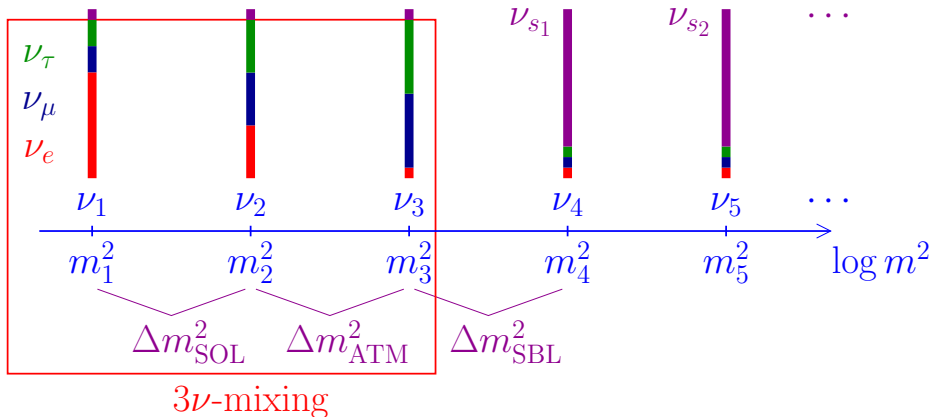
$$|m_{\beta\beta}| \simeq |s_{12}^2 \sqrt{\Delta m_S^2} + e^{i\alpha} s_{13}^2 \sqrt{\Delta m_A^2}|$$

$$\simeq |2.7 + 1.2e^{i\alpha}| \times 10^{-3} \text{ eV}$$

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

$|m_{\beta\beta}| \lesssim 10^{-2} \text{ eV} \Rightarrow$ 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: $L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \quad \tilde{\Phi} = i\sigma_2 \Phi^* = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \xrightarrow[\text{Breaking}]{\text{Symmetry}} \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$

- ▶ SM singlet $\overline{L}_L \tilde{\Phi}$ can couple to new singlet chiral fermion field ν_R (**right-handed neutrino**) related to physics beyond the SM
- ▶ Known examples: SUSY, new symmetries, extra dimensions, mirror world, ... [see http://www.nu.to.infn.it/Sterile_Neutrinos/]
- ▶ **Dirac mass term** $\sim \overline{L}_L \tilde{\Phi} \nu_R$ + **Majorana mass term** $\sim \overline{\nu_R^c} \nu_R$
- ▶ Diagonalization of mass matrix \implies massive Majorana neutrinos

Light Sterile Neutrinos

- ▶ Light anti- ν_R are called **sterile neutrinos**

$$\nu_R^c \rightarrow \nu_{sL} \quad (\text{left-handed})$$

- ▶ Sterile means **no standard model interactions**
- ▶ Active neutrinos (ν_e, ν_μ, ν_τ) 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:

$$\begin{array}{ccccc} \Delta m_{21}^2 & \ll & |\Delta m_{31}^2| & \ll & |\Delta m_{41}^2| \leq \dots \\ \nu_1 & & \nu_2 & & \nu_3 & & \nu_4 & & \dots \\ \nu_e & & \nu_\mu & & \nu_\tau & & \nu_{s1} & & \dots \end{array}$$

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right) \quad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

No CP Violation!

$$P_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right) \quad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

Perturbation of 3 ν 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

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



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

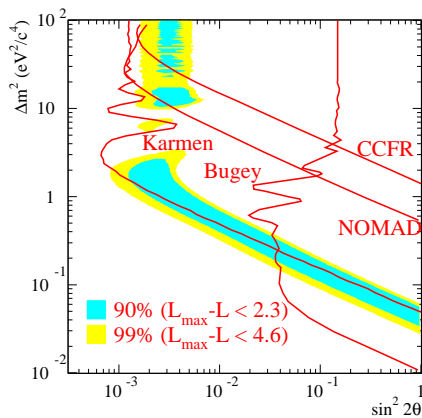
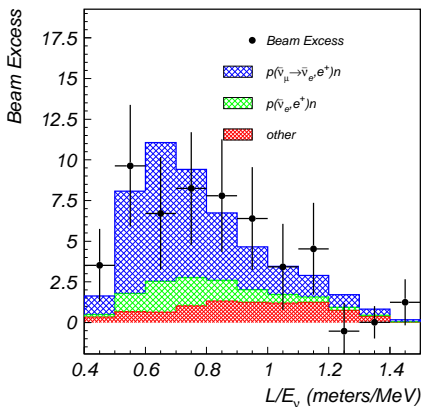
LSND

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

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$L \simeq 30 \text{ m}$$

$$20 \text{ MeV} \leq E \leq 200 \text{ MeV}$$



3.8 σ excess

$$\Delta m_{\text{LSND}}^2 \gtrsim 0.2 \text{ eV}^2 \quad (\gg \Delta m_A^2 \gg \Delta m_S^2)$$

MiniBooNE

$L \simeq 541 \text{ m}$

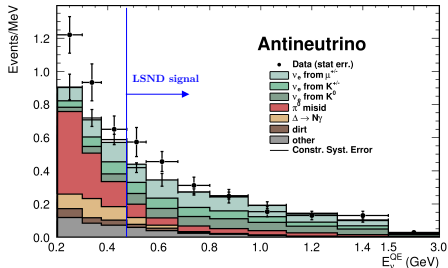
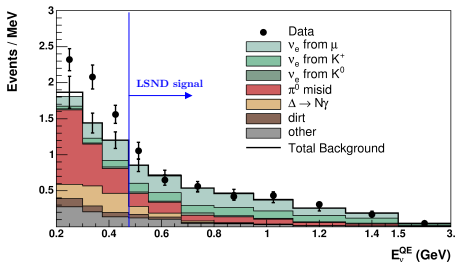
$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$

$\nu_\mu \rightarrow \nu_e$

[PRL 102 (2009) 101802]

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

[PRL 110 (2013) 161801]



▶ Agreement with LSND signal?

▶ CP violation?

▶ Low-energy anomaly!

Neutrino energy reconstruction problem? [Martini, Ericson, Chanfray, PRD 85 (2012) 093012]

Reactor Electron Antineutrino Anomaly

[Mention, Fechner, Lasserre, Mueller,
Lhuillier, Cribier, Letourneau,
PRD 83 (2011) 073006]

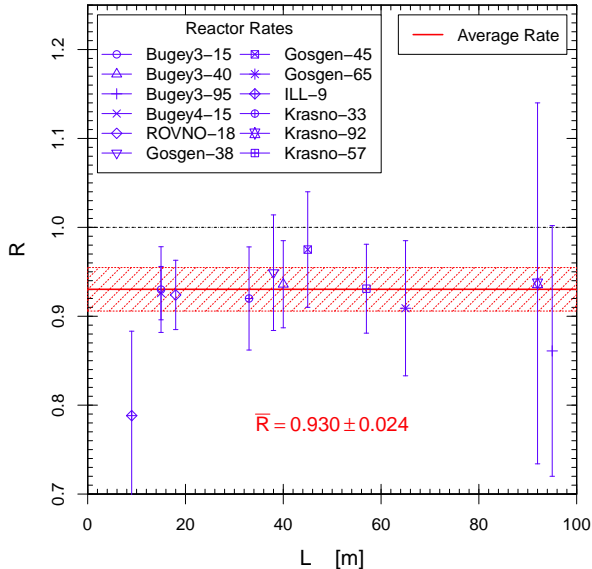
[update in White Paper, arXiv:1204.5379]

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

[Mueller, Lhuillier, Fallot, Letourneau,
Cormon, Fechner, Giot, Lasserre, Martino,
Mention, Porta, Yermia,
PRC 83 (2011) 054615]

[Huber, PRC 84 (2011) 024617]

2.8 σ anomaly



Gallium Anomaly

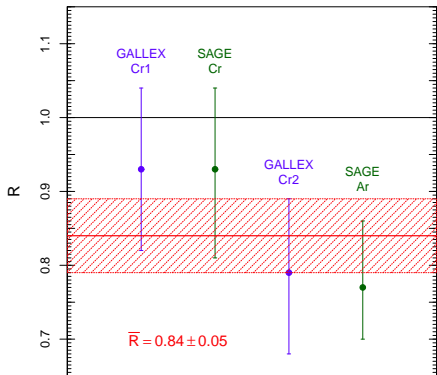
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

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

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

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

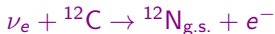
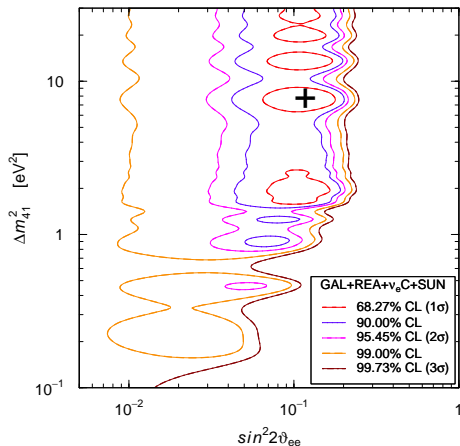
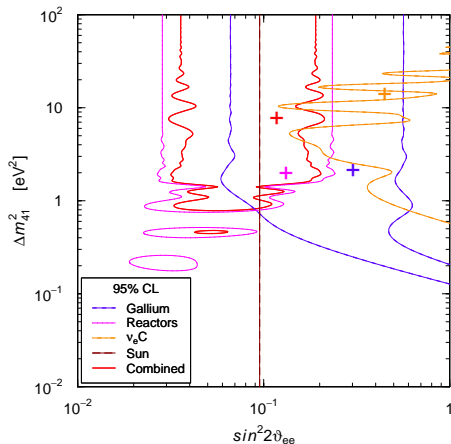
standard parameterization

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

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

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

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



KARMEN + LSND

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

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

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

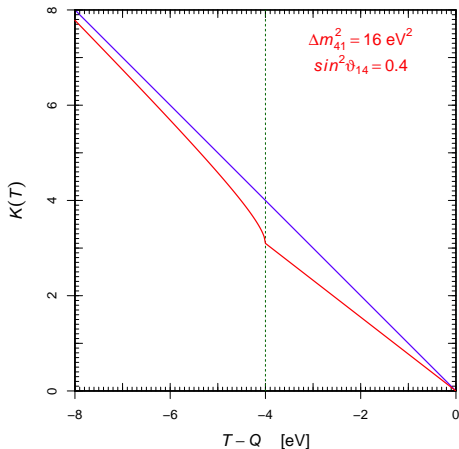
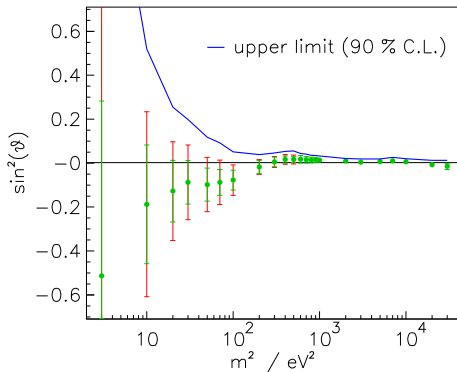
[Giunti, Li, PRD 80 (2009) 113007]

[Palazzo, PRD 83 (2011) 113013]

[Palazzo, PRD 85 (2012) 077301]

Mainz Limit on m_4^2

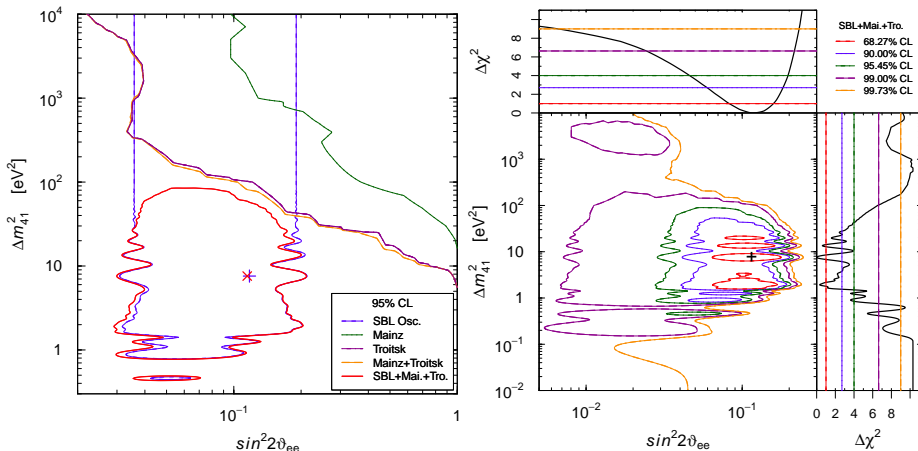
[Kraus, Singer, Valerius, Weinheimer, arXiv:1210.4194]



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

Troitsk: Surprising Much Better Limit on m_{41}^2

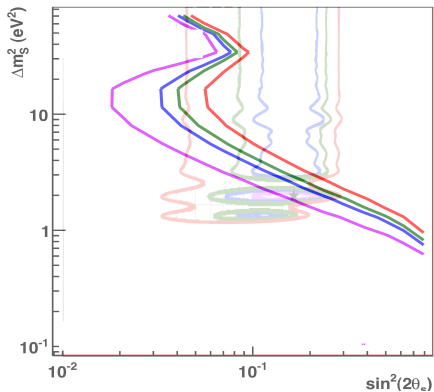
[Belesev, Berlev, Geraskin, Golubev, Likhovid, Nozik, Pantuev, Parfenov, Skasyrskaya, arXiv:1211.7193]



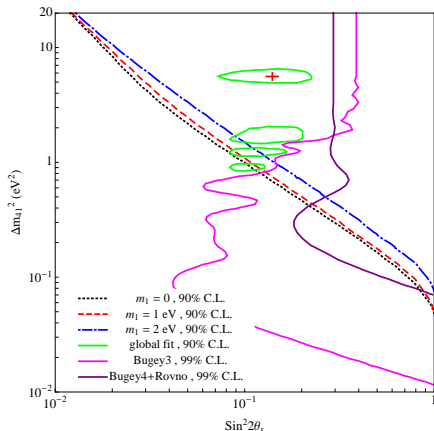
$$2\sigma : 0.85 \lesssim \Delta m_{41}^2 \lesssim 43 \text{ eV}^2 \implies 6 \text{ cm} \lesssim \frac{L_{41}^{\text{osc}}}{E [\text{MeV}]} \lesssim 3 \text{ m}$$

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

KATRIN Sensitivity



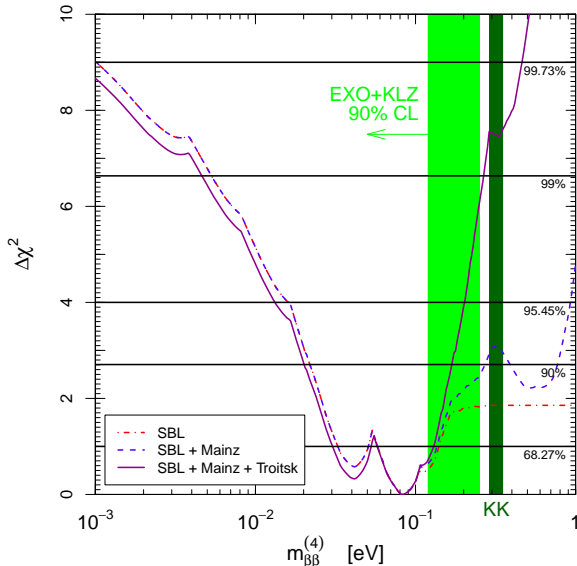
[Formaggio, Barrett, PLB 706 (2011) 68]



[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, JPG 39 (2012) 124008]

3+1: Appearance vs Disappearance

- ▶ ν_e disappearance experiments:

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

- ▶ ν_μ disappearance experiments:

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

- ▶ $\nu_\mu \rightarrow \nu_e$ experiments:

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

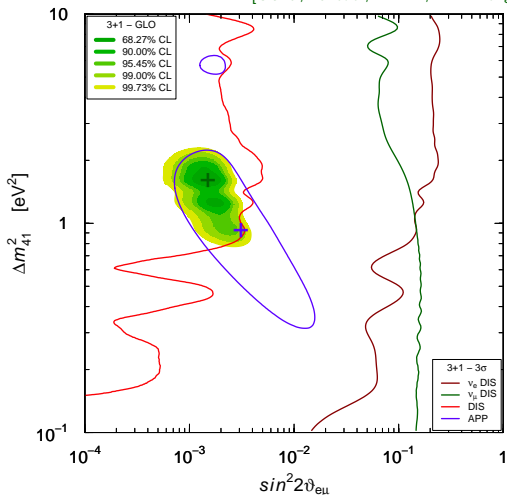
- ▶ Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu} \implies$ strong limit on $\sin^2 2\vartheta_{e\mu}$

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

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

3+1 Global Fit

[Giunti, Laveder, Y.F. Li, H.W. Long, in preparation (2013)]



No Osc. GoF = 1%

3+1 GoF = 33%

PGoF = 10%

▶ APP $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:
LSND (Y), MiniBooNE (?),
OPERA (N), ICARUS (N),
KARMEN (N), NOMAD (N),
BNL-E776 (N)

▶ DIS ν_e & $\bar{\nu}_e$: Reactors (Y),
Gallium (Y), $\nu_e C$ (N),
Solar (N)

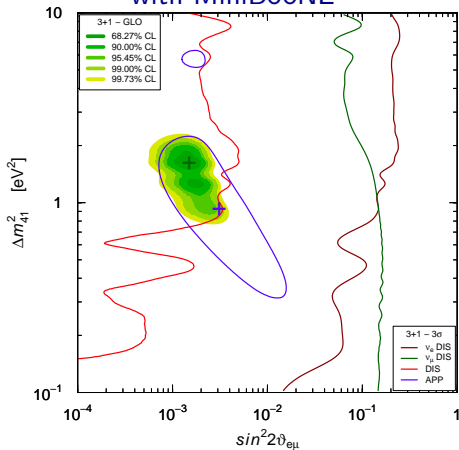
▶ DIS ν_μ & $\bar{\nu}_\mu$: CDHSW (N),
MINOS (N),
Atmospheric (N),
MiniBooNE/SciBooNE (N)

[see also Kopp, Machado,

Maltoni, Schwetz, JHEP 1305 (2013) 050]

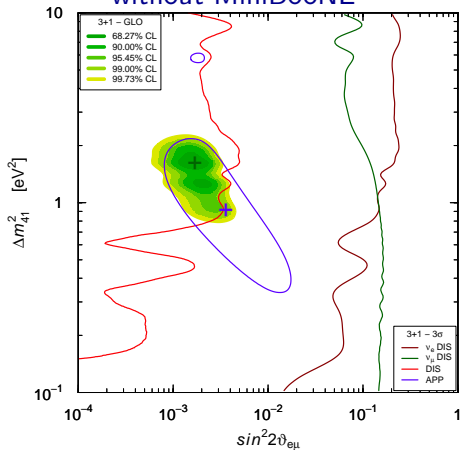
MiniBooNE Impact on SBL Oscillations?

with MiniBooNE



No Osc. GoF = 1%
3+1 GoF = 33%
PGoF = 10%

without MiniBooNE



No Osc. GoF = 0.4%
3+1 GoF = 22%
PGoF = 5%

Cosmology

- ▶ Relativistic energy density before photon decoupling:

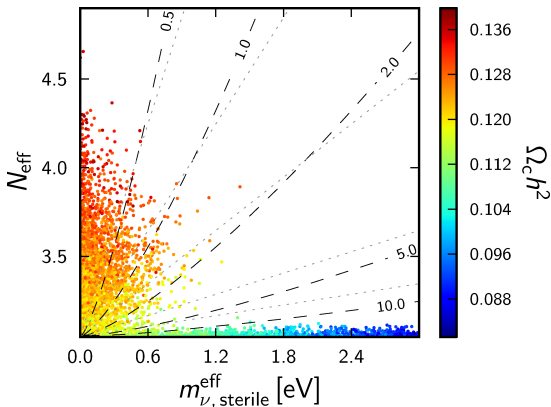
$$\rho_R = \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_\gamma$$

- ▶ N_{eff} = effective neutrino number
- ▶ $N_{\text{eff}} = 3.046 + N_s$
- ▶ N_s = effective number of sterile neutrinos (not necessarily integer)

Planck

[arXiv:1303.5076]

$N_{\text{eff}} < 3.80$ $m_{\nu, \text{sterile}}^{\text{eff}} < 0.42$ (95%; CMB + BAO)



▶ $m_{\nu, \text{sterile}}^{\text{eff}} \equiv 94.1 \omega_{\nu_4} \text{ eV}$

▶ Thermally distributed:

$$f_s(E) = \frac{1}{e^{E/T_s} + 1}$$

$$m_{\nu, \text{sterile}}^{\text{eff}} = \left(\frac{T_s}{T_\nu} \right)^3 m_4 \\ = (\Delta N_{\text{eff}})^{3/4} m_4$$

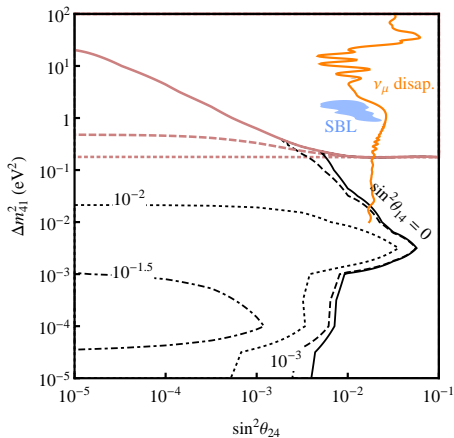
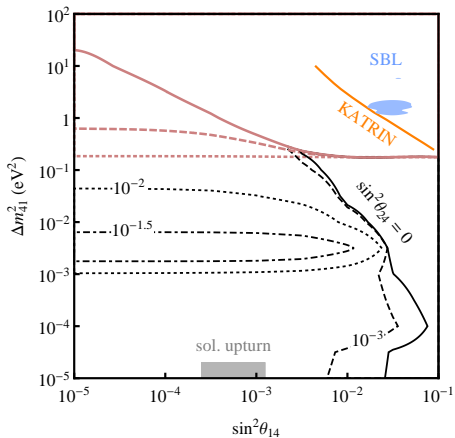
▶ Dodelson-Widrow:

$$f_s(E) = \frac{\chi}{e^{E/T_\nu} + 1}$$

$$m_{\nu, \text{sterile}}^{\text{eff}} = \chi_s m_4$$

Standard Cosmological Scenario Mixing Bounds

[Mirizzi, Mangano, Saviano, Borriello, Giunti, Miele, Pisanti, arXiv:1303.5368]



Non-standard mechanism for partial thermalization of ν_s is needed
Large primordial neutrino asymmetry?

[Hannestad, Tamborra, Tram, JCAP 1207 (2012) 025; Mirizzi, Saviano, Miele, Serpico, PRD 86 (2012) 053009;
Saviano, Mirizzi, Pisanti, Serpico, Mangano, Miele, PRD 87 (2013) 073006]

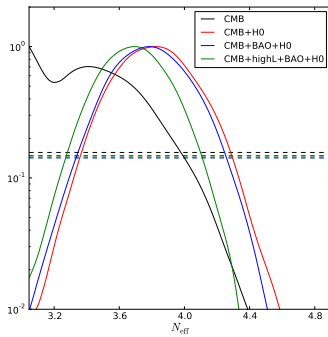
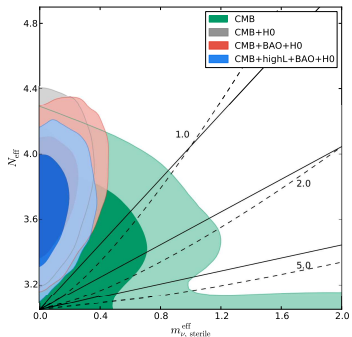
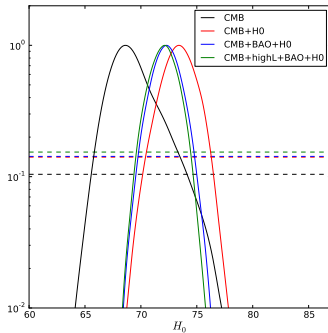
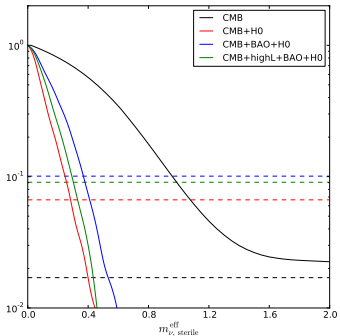
CMB + H_0

[Gariazzo, Giunti, Laveder, in preparation (2013)]

$$H_0 = \left\{ \begin{array}{ll} 67.4 \pm 1.4 & \text{Planck} \\ 70.0 \pm 2.2 & \text{WMAP-9} \\ 73.8 \pm 2.4 & \text{Cepheids+SN Ia} \\ 74.3 \pm 2.6 & \text{Carnegie HP} \\ 78.7 \pm 4.5 & \text{COSMOGRAIL} \end{array} \right\} [\text{kms}^{-1}\text{Mpc}^{-1}]$$

Gaussian Prior: $H_0 = 74.7 \pm 1.6 \text{ kms}^{-1}\text{Mpc}^{-1}$

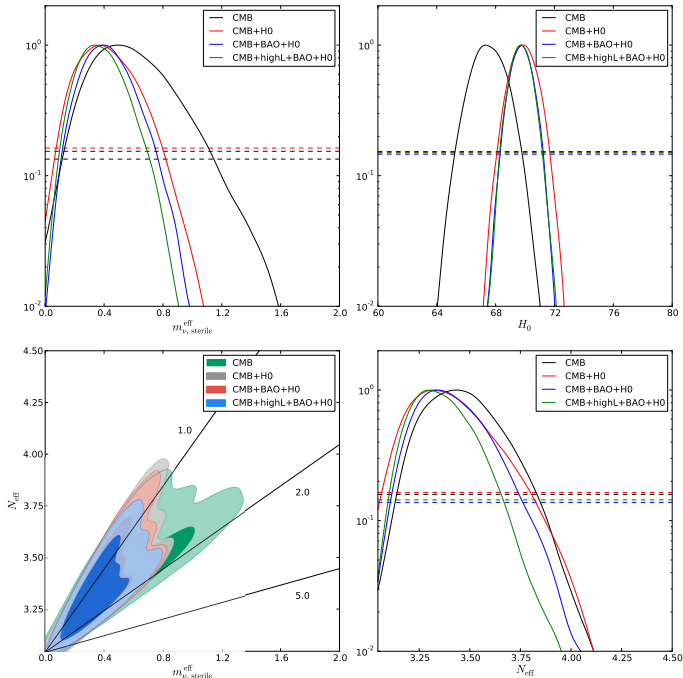
weighted average of Cepheids+SN Ia, Carnegie HP, COSMOGRAIL



$3.16 < N_{\text{eff}} < 4.24$ (99%)

$m_{\nu, \text{sterile}}^{\text{eff}} < 0.41 \text{ eV}$ (99%)

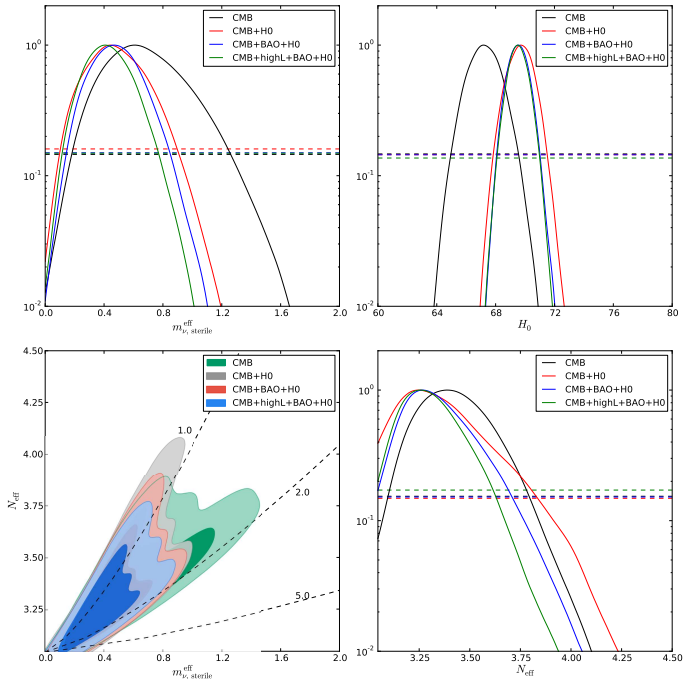
SBL Prior - Dodelson-Widrow



$N_{\text{eff}} < 3.80$ (99%)

$0.042 < m_{\nu, \text{sterile}}^{\text{eff}} < 0.81 \text{ eV}$ (99%)

SBL Prior - Thermal



$N_{\text{eff}} < 3.79$ (99%)

$0.049 < m_{\nu, \text{sterile}}^{\text{eff}} < 0.90 \text{ eV}$ (99%)

Conclusions

- ▶ Robust Three-Neutrino Mixing Paradigm. Open problems: $\vartheta_{23} < 45^\circ?$, CP Violation, Mass Hierarchy, Absolute Mass Scale, Dirac or Majorana?
- ▶ Short-Baseline ν_e and $\bar{\nu}_e$ 3+1 Disappearance:
 - ▶ Reactor $\bar{\nu}_e$ and Gallium ν_e anomalies are alive and exciting
 - ▶ 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 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ LSND Signal:
 - ▶ MiniBooNE experiment has been inconclusive
 - ▶ If $|U_{e4}| > 0$ why not $|U_{\mu4}| > 0$? \implies Maybe LSND luckily observed a fluctuation of a small $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transition probability with amplitude $\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$, not seen by other appearance experiments
 - ▶ Better experiments are needed to check LSND signal
- ▶ Cosmology:
 - ▶ Tension between Planck H_0 and direct measurements
 - ▶ $N_{\text{eff}} = 4$ is not excluded (CMB + HigL + BAO + H_0)
 - ▶ Strong constraints on mass: $m_{\nu, \text{sterile}}^{\text{eff}} < 0.41 \text{ eV}$ (99%)
 - ▶ Cosmology + SBL: $m_4 \simeq \Delta m_{41}^2 \simeq 1 \text{ eV}^2$ and $N_{\text{eff}} < 3.8$ (99%)
 - ▶ Mechanis for partial thermalization of ν_s is needed

Backup Slides

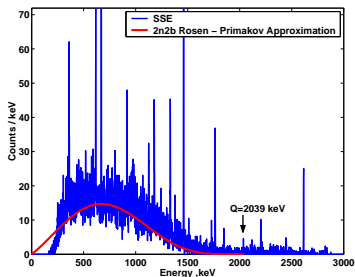
Experimental Positive Indication of $\beta\beta_{0\nu}$ -Decay

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

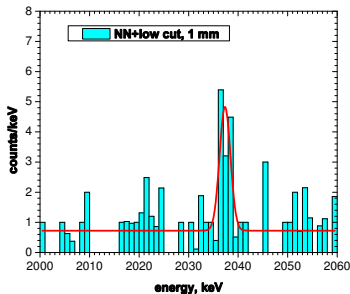
$$T_{1/2}^{0\nu} = (2.23_{-0.31}^{+0.44}) \times 10^{25} \text{ y}$$

6.5 σ evidence

[MPLA 21 (2006) 1547]



[PLB 586 (2004) 198]



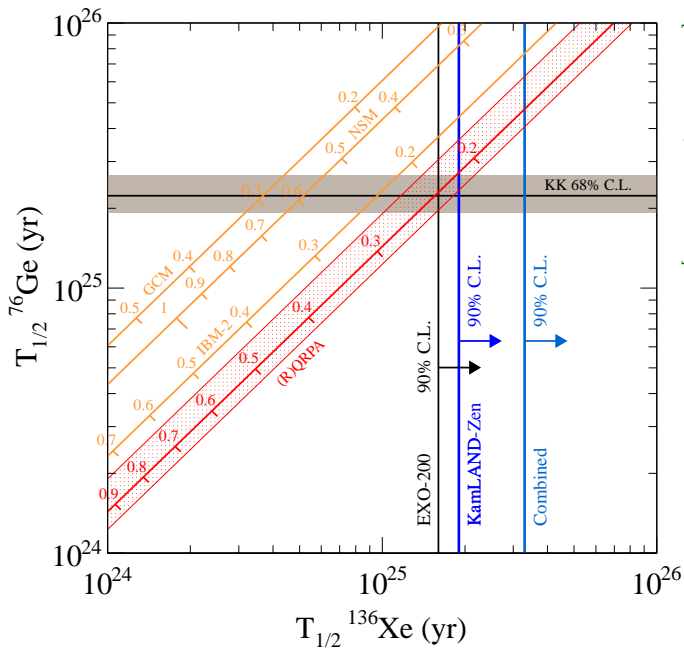
[MPLA 21 (2006) 1547]

$$|m_{\beta\beta}| = 0.32 \pm 0.03 \text{ eV}$$

[MPLA 21 (2006) 1547]

very exciting: Majorana ν and large mass scale

partially excluded by KamLAND-Zen, EXO and CUORICINO



[KamLAND-Zen, arXiv:1211.3863]

Effective SBL Oscillation Probabilities in 3+2 Schemes

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

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

$$P_{\nu_{\mu} \rightarrow \nu_e}^{(-) \quad (-)} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \phi_{51} + 8|U_{\mu 4} U_{e4} U_{\mu 5} U_{e5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} \overset{(+)}{-} \eta)$$

$$P_{\nu_{\alpha} \rightarrow \nu_{\alpha}}^{(-) \quad (-)} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 \phi_{41} + |U_{\alpha 5}|^2 \sin^2 \phi_{51}) - 4|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 \phi_{54}$$

[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, JHEP 07 (2012) 161; Conrad, Ignarra, Karagiorgi, Shaevitz, Spitz, AHEP 2013 (2013) 163897; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

▶ Good: CP violation

▶ Bad: 4 more parameters: $\underbrace{\Delta m_{41}^2, |U_{e4}|^2, |U_{\mu 4}|^2, \Delta m_{51}^2, |U_{e5}|^2, |U_{\mu 5}|^2, \eta}_{3+1}$

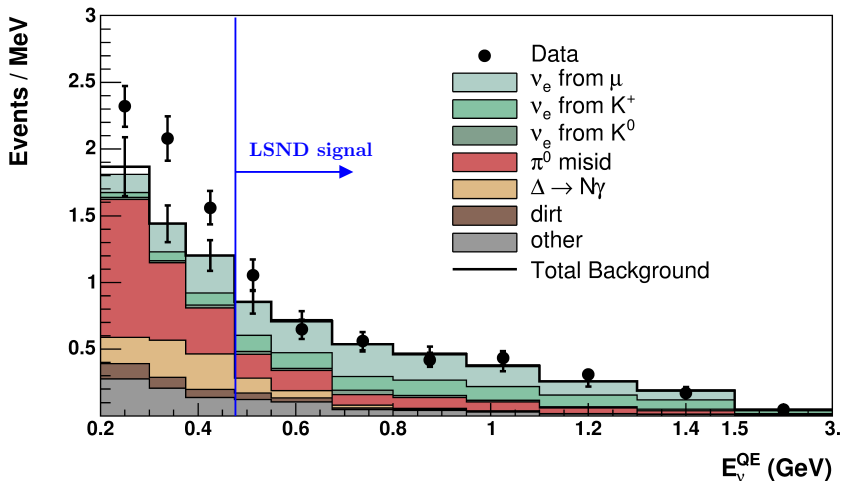
MiniBooNE Neutrinos - 2008

[PRL 102 (2009) 101802, arXiv:0812.2243]

$\nu_\mu \rightarrow \nu_e$

$L \simeq 541$ m

$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$



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

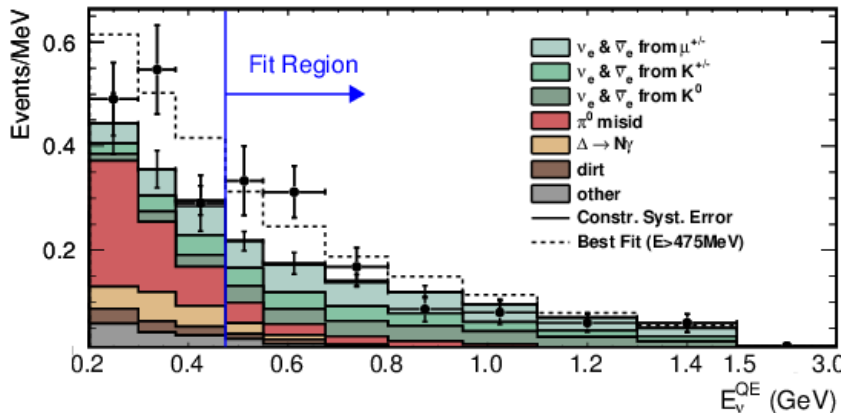
MiniBooNE Antineutrinos - 2010

[PRL 105 (2010) 181801, arXiv:1007.1150]

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

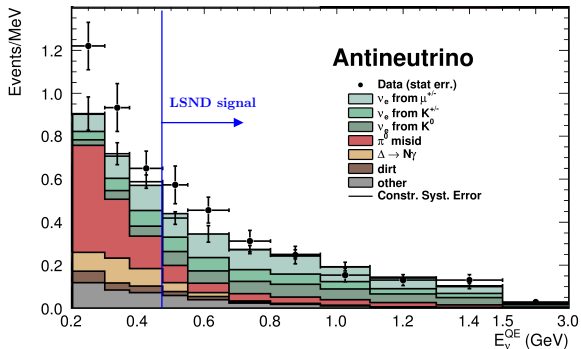
$$L \simeq 541 \text{ m}$$

$$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$$



- ▶ agreement with LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal ($E > 475 \text{ MeV}$)
- ▶ similar L/E but different L and $E \implies$ 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)

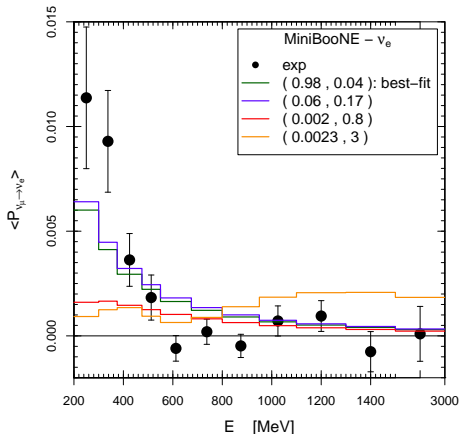
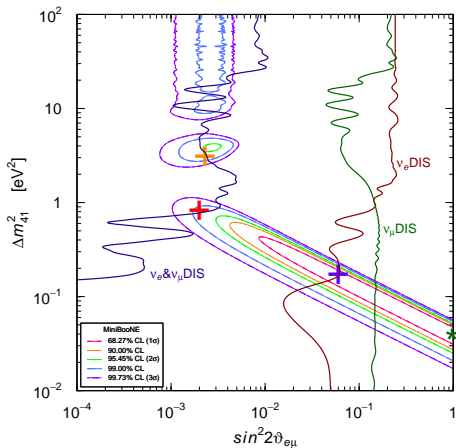
? agreement with LSND signal ? CP violation ?

? nevertheless, claim of evidence of oscillations of ν and $\bar{\nu}$?

? mainly from low-energy excess (contradiction with 2009 ν -data paper) ?

[arXiv:1207.4809, duplicated in arXiv:1303.2588 → PRL 110 (2013) 161801]

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



- ▶ Fit of low-energy excess is marginal for $\Delta m_{41}^2 \lesssim 0.4 \text{ eV}^2$
- ▶ No fit of low-energy excess for realistic $\Delta m_{41}^2 \gtrsim 0.8 \text{ eV}^2$
- ▶ Neutrino energy reconstruction problem?

[Martini, Ericson, Chanfray, PRD 85 (2012) 093012]

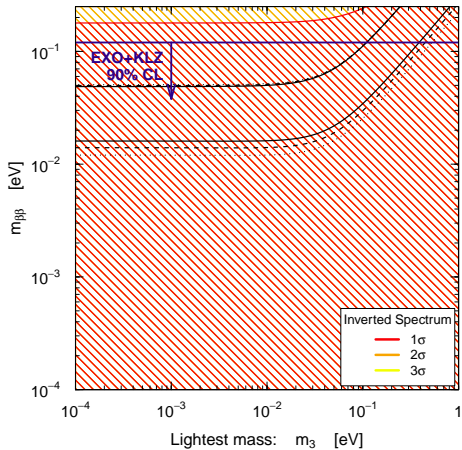
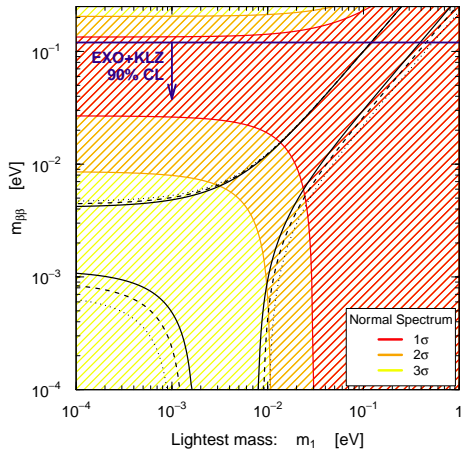
Cancellation with $m_{\beta\beta}^{(\text{light})}$?

[Barry, Rodejohann, Zhang, JHEP 07 (2011) 091]; Li, Liu, PLB 706 (2012) 406; Rodejohann, JPG 39 (2012) 124008]

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

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

- ▶ **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



Assumption: no cancellation

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

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

