Sterile Neutrinos in July 2010

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Presidenza INFN, Roma, 19 July 2010

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Standard Model: Massless Neutrinos

- Standard Model: $\nu_L, \nu_R^c \quad \Longrightarrow \quad$ no Dirac mass term

$$\mathcal{L}^{\mathrm{D}} = m^{\mathrm{D}} \left(\overline{\nu_L} \nu_R + \overline{\nu_R} \nu_L \right)$$

- Majorana Neutrino: $\nu^c = \nu$

- $\nu_R^c = \nu_R \quad \Longrightarrow \quad$ Majorana mass term

$$\mathcal{L}^{\mathrm{M}} = \frac{1}{2} m^{\mathrm{M}} \left(\overline{\nu_L} \nu_R^c + \overline{\nu_R^c} \nu_L \right)$$

- Standard Model: Majorana mass term not allowed by $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

(no Higgs triplet)

- Neutrinos are special in the Standard Model: the only neutral fermions

- In extensions of SM neutrinos can mix with non-SM fermions

$$L_{\alpha L} = \begin{pmatrix} \nu_{\alpha L} \\ \alpha_L \end{pmatrix} \qquad \widetilde{\Phi} = i\sigma_2 \, \Phi^* = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \xrightarrow[\text{Breaking}]{\text{Symmetry}} \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$$

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

$\overline{L_{\alpha L}} \widetilde{\Phi}$ can be coupled to new non-SM chiral fermion fields $f_{\beta R}$

Dirac mass terms $\sim \overline{L_{\alpha L}} \widetilde{\Phi} f_{\beta R}$ $+$ Majorana mass terms $\sim \overline{f_{\beta R}^{C}} f_{\beta R}$

$f_{\beta R}$ are often called Right-Handed Neutrinos: $f_{\beta R} \to \nu_{\beta R}$

- If $f_{\beta R}$ are light, they are called Sterile Neutrinos:

$$\nu_{s_\beta L} = f_{\beta R}^{C}$$

Sterile Neutrinos

- Sterile means No Standard Model Interactions

- Obviously no electromagnetic interactions as normal active neutrinos

- Thus Sterile means No Standard Weak Interactions

- But Sterile Neutrinos are not absolutely sterile:
  - Gravitational Interactions
  - New Non-Standard Interactions of the Physics Beyond the Standard Model which generates the masses of sterile neutrinos

- Extremely interesting and powerful window on Physics Beyond the SM

- Active Neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into Sterile Neutrinos (ν_s)

- Observable: disappearance of Active Neutrinos or indirect evidence through combined fit of data

How many Sterile Neutrinos?

$e^+ e^- \to Z \to \nu\bar{\nu} \quad \Rightarrow \quad \nu_e \;\; \nu_\mu \;\; \nu_\tau$ 3 active flavor neutrinos

mixing $\Rightarrow \quad \nu_{\alpha L} = \sum_{k=1}^{N} U_{\alpha k} \nu_{kL} \qquad \alpha = e, \mu, \tau$

$N \geq 3$
no upper limit!

$$\begin{array}{lcccccc}
\text{Mass Basis:} & \nu_1 & \nu_2 & \nu_3 & \nu_4 & \nu_5 & \cdots \\
\text{Flavor Basis:} & \nu_e & \nu_\mu & \nu_\tau & \nu_{s_1} & \nu_{s_2} & \cdots
\end{array}$$

ACTIVE STERILE

Experimental Evidences of Neutrino Oscillations

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

Reactor
$\bar{\nu}_e$ disappearance

Homestake
Kamiokande
GALLEX/GNO & SAGE
Super-Kamiokande
SNO
BOREXino

(KamLAND)

→

$$\begin{cases} \Delta m^2_{\text{SOL}} \simeq 7.6 \times 10^{-5} \, \text{eV}^2 \\ \sin^2 \vartheta_{\text{SOL}} \simeq 0.32 \end{cases}$$

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

Accelerator
ν_μ disappearance

Kamiokande
IMB
Super-Kamiokande
MACRO
Soudan-2

(K2K & MINOS)

→

$$\begin{cases} \Delta m^2_{\text{ATM}} \simeq 2.4 \times 10^{-3} \, \text{eV}^2 \\ \sin^2 \vartheta_{\text{ATM}} \simeq 0.50 \end{cases}$$

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

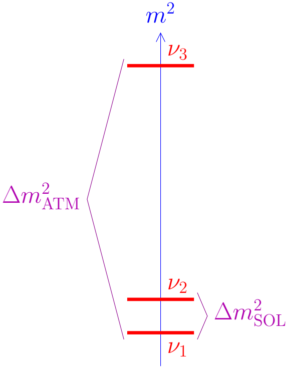
three massive fields: ν_1, ν_2, ν_3

$$\Delta m^2_{21} + \Delta m^2_{32} + \Delta m^2_{13} = m^2_2 - m^2_1 + m^2_3 - m^2_2 + m^2_1 - m^2_3 = 0$$

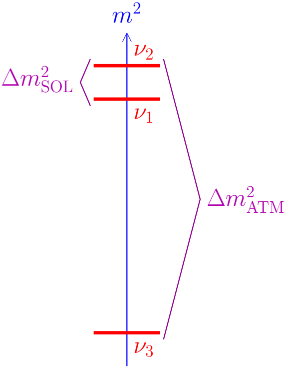
$$\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$$

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

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

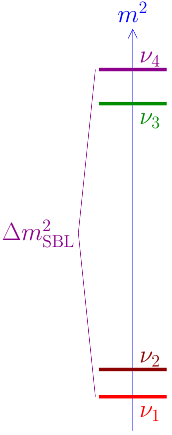
- Interesting possibility: a new $\Delta m^2_{\mathrm{SBL}} \gtrsim 1\,\mathrm{eV}^2$
- It has been studied in connection with searches of neutrino oscillations in Short-BaseLine Experiments

$$\frac{L}{E} \lesssim 1\,\frac{\mathrm{m}}{\mathrm{MeV}} \qquad \Longrightarrow \qquad \Delta m^2_{\mathrm{SBL}} \gtrsim 1\,\mathrm{eV}^2$$

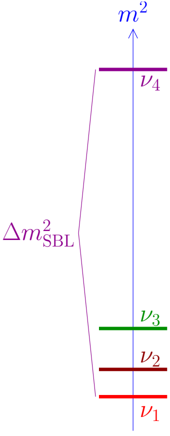
- Necessary introduction of at least one new massive neutrino: 4-ν Mixing

$$\Delta m^2_{\mathrm{SBL}} = \Delta m^2_{41}$$

Four-Neutrino Schemes: 2+2 and 3+1



"2+2"

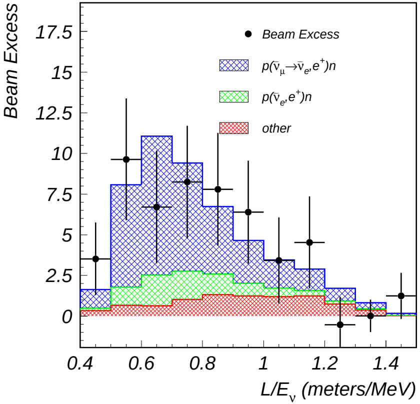


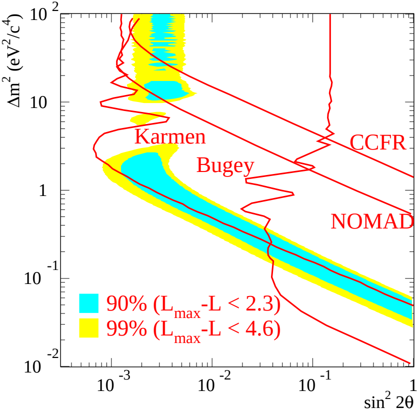
"3+1"

LSND

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

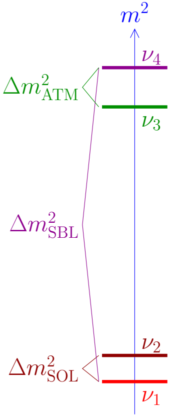
$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 30\,\mathrm{m}$ $\quad 20\,\mathrm{MeV} \leq E \leq 200\,\mathrm{MeV}$



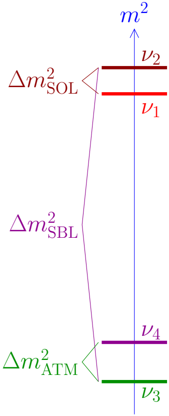


$$\Delta m^2_{\mathrm{LSND}} \gtrsim 0.2\,\mathrm{eV}^2 \qquad (\gg \Delta m^2_{\mathrm{ATM}} \gg \Delta m^2_{\mathrm{SOL}})$$

2+2 Four-Neutrino Schemes

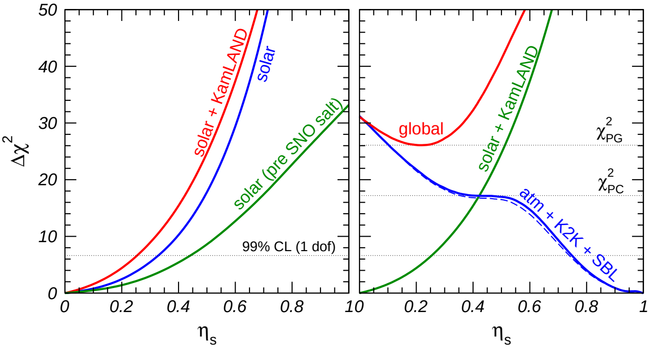


"normal"



"inverted"

2+2 Schemes are strongly disfavored by solar and atmospheric data

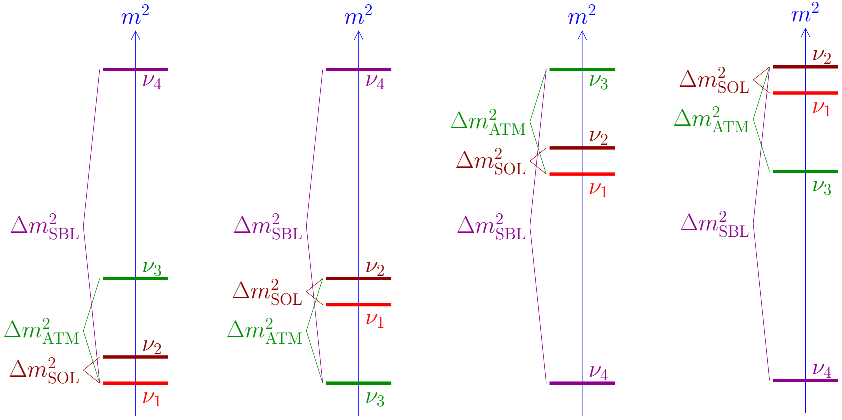


[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

$\eta_s = |U_{s1}|^2 + |U_{s2}|^2$

99% CL: $\begin{cases} \eta_s < 0.25 & \text{(solar + KamLAND)} \\ \eta_s > 0.75 & \text{(atmospheric + K2K)} \end{cases}$

3+1 Four-Neutrino Schemes



"normal" "3ν-inverted" "4ν-inverted" "fully-inverted"

Perturbation of 3-ν Mixing

$|U_{e4}|^2 \ll 1$ $|U_{\mu4}|^2 \ll 1$ $|U_{\tau4}|^2 \ll 1$ $|U_{s4}|^2 \simeq 1$

Effective SBL Oscillation Probability in 3+1 Schemes

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

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

No CP Violation!

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

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

$$U = \left(\begin{array}{ccc|c|} \hline U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \\ \hline \end{array}\right)$$

$\uparrow$

SBL

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

$$\Downarrow$$

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

- 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:

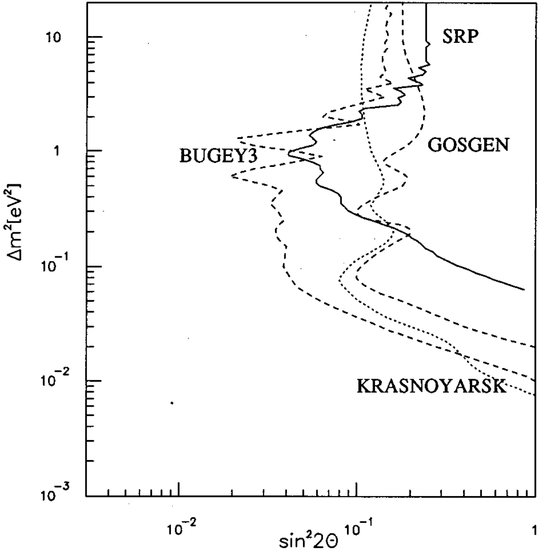
$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 \left(1 - |U_{\mu4}|^2\right) \simeq 4|U_{\mu4}|^2$$

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

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

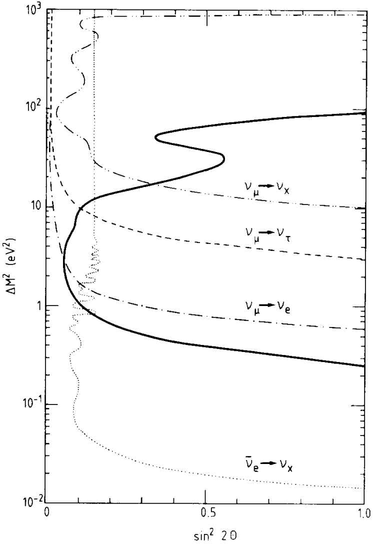
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ imply strong limit on $\sin^2 2\vartheta_{e\mu}$

$\bar{\nu}_e$ Disappearance

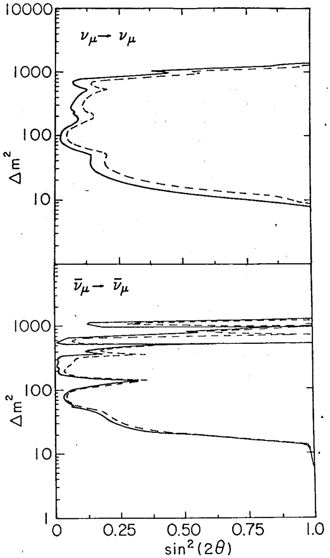


[Savannah River (SRP), PRD 53 (1996) 6054]

$\overset{(-)}{\nu}_{\mu}$ Disappearance

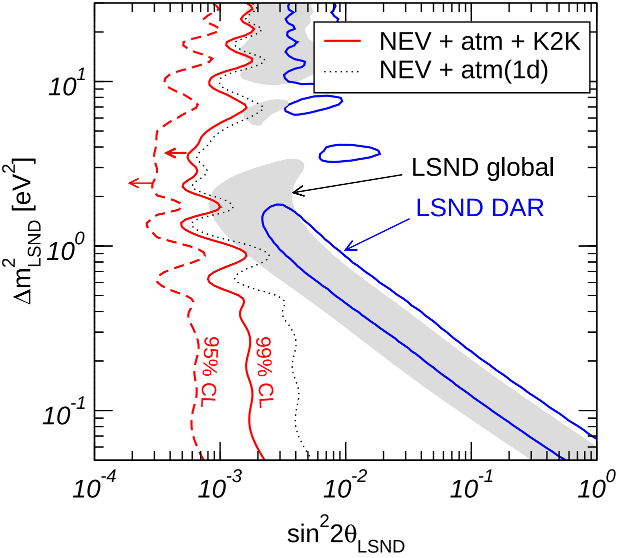


[CDHSW, PLB 134 (1984) 281]



[CCFR, Z. Phys. C 27 (1985) 53]

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$

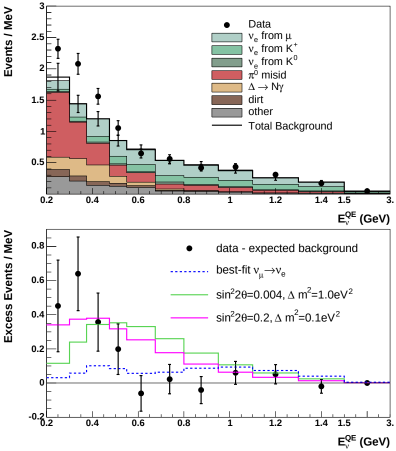


[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

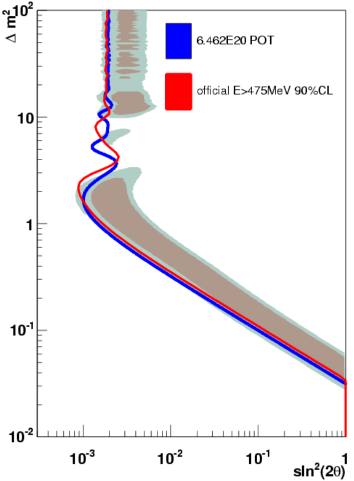
MiniBooNE Neutrinos

[PRL 98 (2007) 231801]

$\nu_\mu \to \nu_e$ $\quad L \simeq 541\,\text{m} \quad 475\,\text{MeV} \le E \lesssim 3\,\text{GeV}$



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



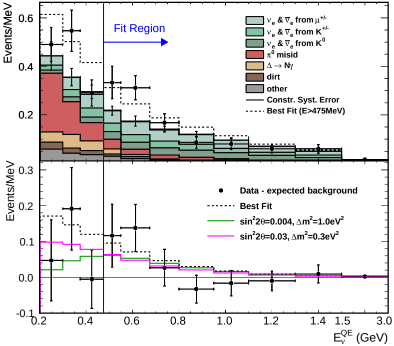
[arXiv:0901.1648]

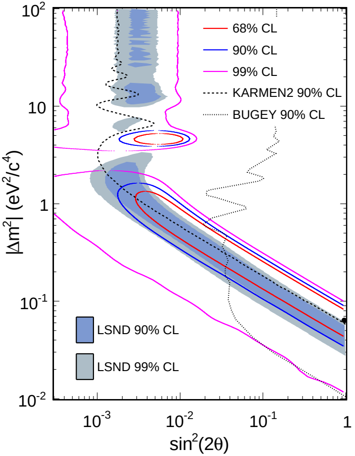
Low-Energy Anomaly!

MiniBooNE Antineutrinos

[arXiv:1007.1150]

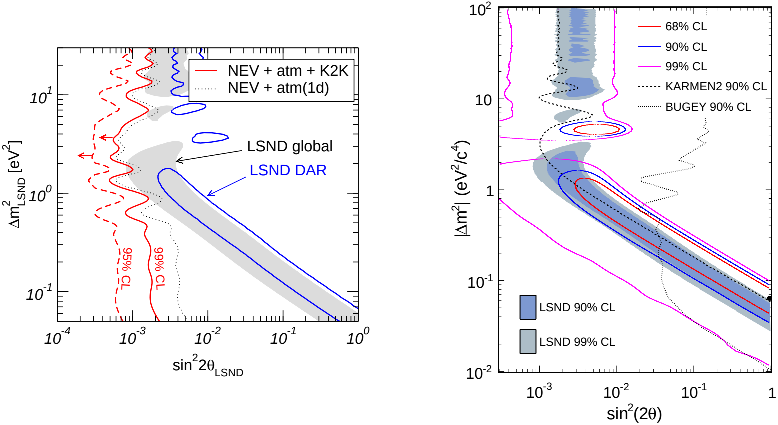
$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 541\,\text{m}$ $\quad 475\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$





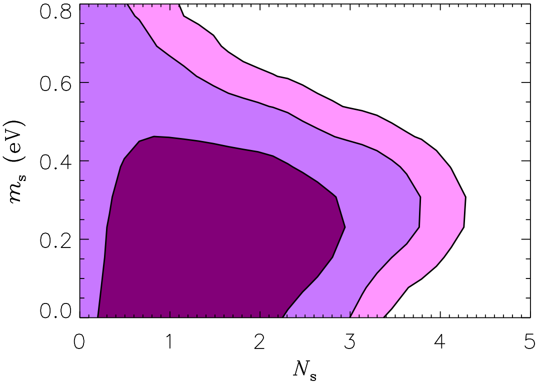
Agreement with LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal!

Similar L/E but different L and E $\Longrightarrow$ Oscillations!



- Most of LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ allowed region excluded by MiniBooNE $\nu_\mu \to \nu_e$
- Tension between LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance and $\bar{\nu}_e$ (Bugey) + $\overset{(-)}{\nu}_\mu$ (CDHSW+CCFR) disappearance limits
- Marginally preferred: $\Delta m^2_{\text{SBL}} \simeq 0.9\,\text{eV}^2$ $\sin^2 2\vartheta_{e\mu} \simeq 2 \times 10^{-3}$

- $m_1 \ \ m_2 \ \ m_3 \ll m_4 \quad \Longrightarrow \quad m_4 \simeq \sqrt{\Delta m^2_{41}} = \Delta m^2_{\text{SBL}}$
- $\Delta m^2_{\text{SBL}} \simeq 0.9\,\text{eV}^2 \quad \Longrightarrow \quad m_4 \simeq 0.9\,\text{eV}$
- Marginally allowed by cosmological limit in ΛCDM (thermalized ν_s's)

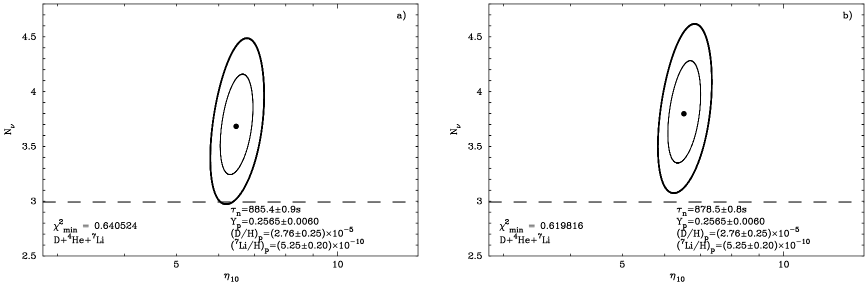


[Hamann, Hannestad, Raffelt, Tamborra, Wong, arXiv:1006.5276]

- Note preference for $N_s > 0$ indicated also by BBN

The primordial abundance of ^{4}He: evidence for non-standard BBN

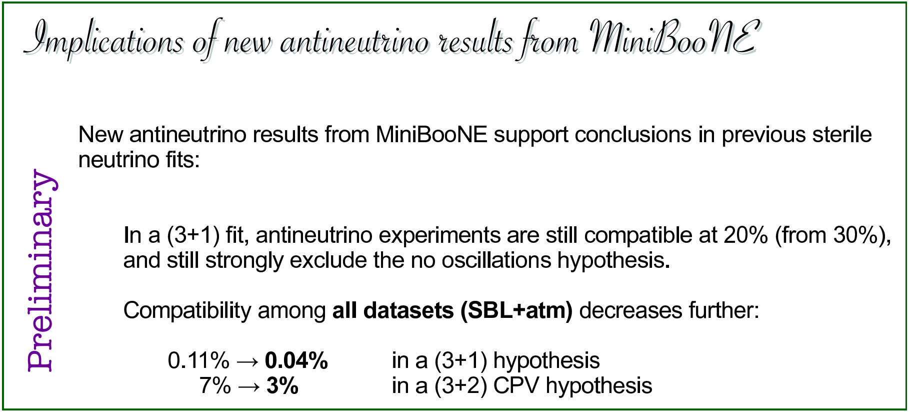
[Izotov, Thuan, Astrophysical Journal Letters 710 (2010) L67, arXiv:1001.4440]



$$N_\nu = 3.68^{+0.80}_{-0.70} \qquad\qquad N_\nu = 3.80^{+0.80}_{-0.70}$$

$$(2\sigma)$$

3+2 Five-Neutrino Mixing?



Implications of new antineutrino results from MiniBooNE

Preliminary

New antineutrino results from MiniBooNE support conclusions in previous sterile neutrino fits:

In a (3+1) fit, antineutrino experiments are still compatible at 20% (from 30%), and still strongly exclude the no oscillations hypothesis.

Compatibility among **all datasets (SBL+atm)** decreases further:

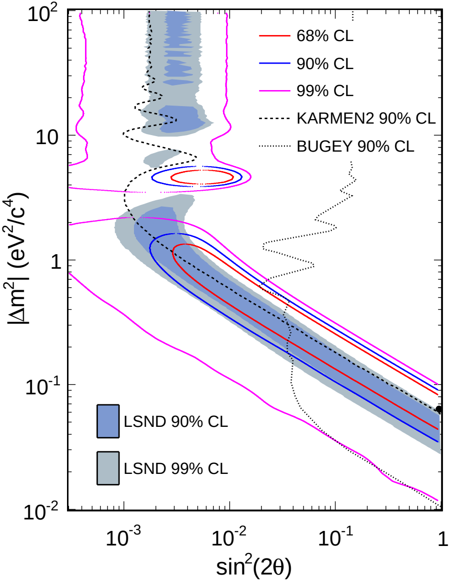
0.11% → **0.04%**	in a (3+1) hypothesis
7% → **3%**	in a (3+2) CPV hypothesis

[Georgia Karagiorgi, Neutrino 2010, 14 June 2010]

CPT Violation?

- Masses and mixing of neutrinos and antineutrinos may be different
- In CDHSW mainly ν_μ's
- No limit on SBL $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions from disappearance experiments

  [Barger, Marfatia, Whisnant, PLB 576 (2003) 303]
- LSND and MiniBooNE allowed regions are limited only by KARMEN and Bugey



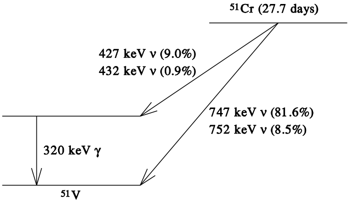
Gallium Anomaly

Gallium Radioactive Source Experiments

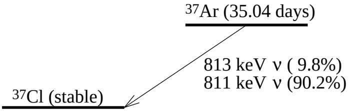
Tests of the solar neutrino detectors GALLEX (Cr1, Cr2) and SAGE (Cr, Ar)

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

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



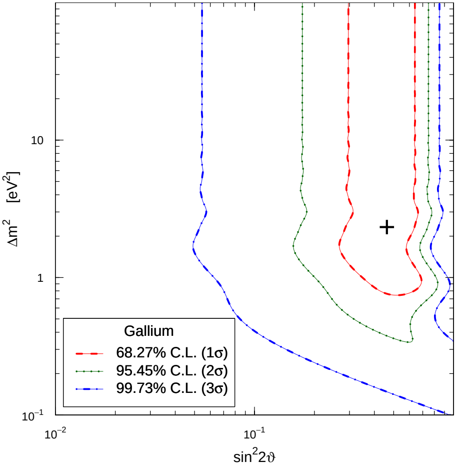
[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]



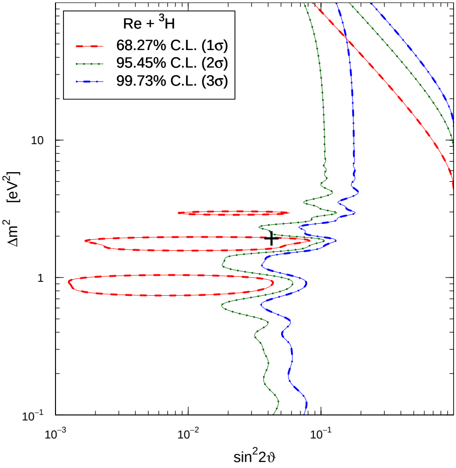
[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

$$\boxed{R_{\text{Ga}} = 0.76^{+0.09}_{-0.08}}$$

[Giunti, Laveder, arXiv:1006.3244]



[Giunti, Laveder, arXiv:1006.3244]



[Giunti, Laveder, arXiv:1005.4599]

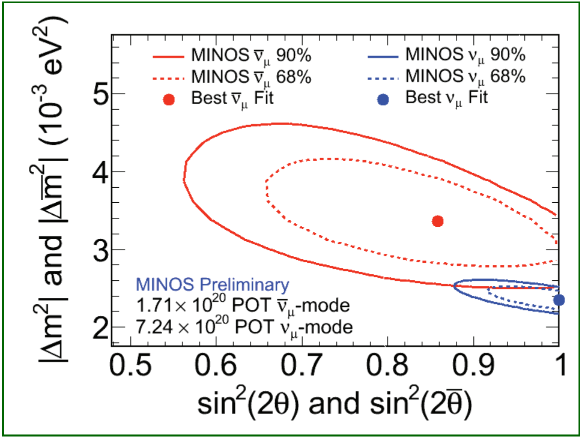
$\Delta m^2_{\text{SBL}} \simeq 0.9\,\text{eV}^2$ is OK

$\sin^2 2\vartheta_{\nu} > \sin^2 2\vartheta_{\bar{\nu}}$ CPT violation?

MINOS Hint of CPT Violation

LBL ν_μ disappearance $E \sim 3\,\mathrm{GeV}$

Near Detector at 1.04 km Far Detector at 734 km

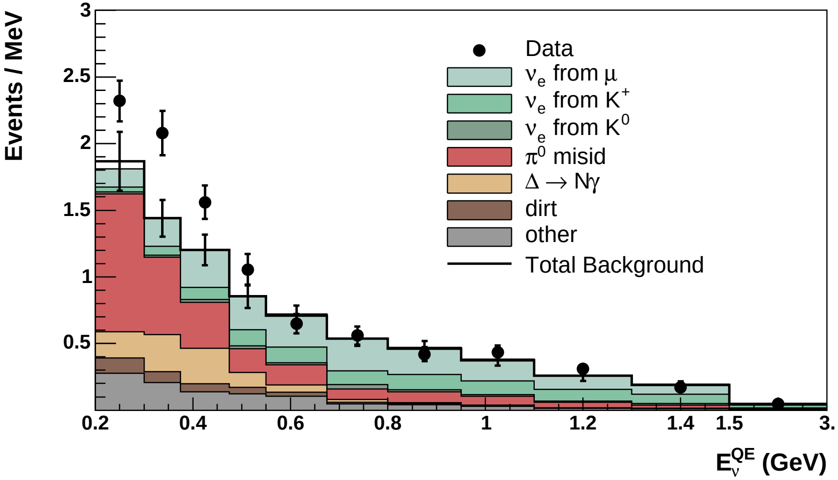


[MINOS, Neutrino 2010, 14 June 2010]

Conclusions

- Existence of sterile neutrinos is possible and likely connected with neutrino mass generation
- Impressive LSND and MiniBooNE agreement on $\bar{\nu}_\mu \to \bar{\nu}_e$ signal
- Three experimental tensions:
  - LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ vs MiniBooNE $\nu_\mu \to \nu_e$
  - LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ vs $\bar{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ disappearance limits
  - Gallium Anomaly (ν_e disappearance) vs Bugey ($\bar{\nu}_e$ disappearance)
- Interpretation of experimental results is difficult:
  - 3+1 Four-Neutrino Mixing or more?
  - CPT violation?
  - ...?
- ΛCDM cosmology and BBN indicate $N_s > 0$
- New experiments are needed!

MiniBooNE Low-Energy Anomaly



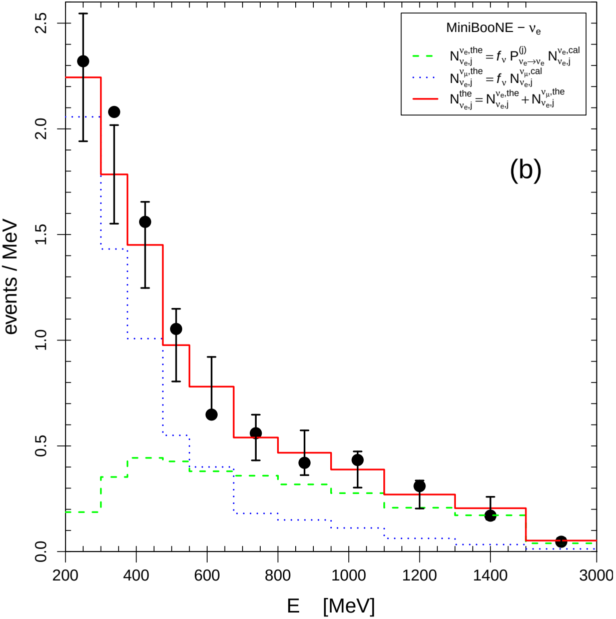
[PRL 102 (2009) 101802, arXiv:0812.2243]

Our Hypothesis: $N^{\text{the}}_{\nu,j} = f_\nu \left(P_{\nu_e \to \nu_e} N^{\text{cal}}_{\nu_e,j} + N^{\text{cal}}_{\nu_\mu,j} \right)$

[Giunti, Laveder, PRD 77 (2008) 093002, arXiv:0707.4593; PRD 80 (2009) 013005, arXiv:0902.1992]

$$\boxed{N^{\text{the}}_{\nu,j} = f_\nu \left(P_{\nu_e\to\nu_e} N^{\text{cal}}_{\nu_e,j} + N^{\text{cal}}_{\nu_\mu,j} \right)}$$

- Estimated 15% uncertainty of the calculated neutrino flux [MiniBooNE, PRD 79 (2009) 072002, arXiv:0806.1449] is consistent with measured ratio 1.21 ± 0.24 of detected and predicted charged-current quasi-elastic ν_μ events [MiniBooNE, PRL 100 (2008) 032301, arXiv:0706.0926]
- We fit MiniBooNE ν_e and ν_μ data using the info at `http://www-boone.fnal.gov/for_physicists/data_release/lowe/`



[Giunti, Laveder, 2010, arXiv:1005.4599]

No Osc. & $f_\nu = 1$

$\chi^2_{\text{min}} = 14.3 + 5.4$

$\text{NdF} = 3 + 16$

$\text{GoF} = 41\%$

Our Hypothesis

$\chi^2_{\text{min}} = 2.0 + 7.6$

$\text{NdF} = 16$

$\text{GoF} = 89\%$

$f_\nu = 1.26$

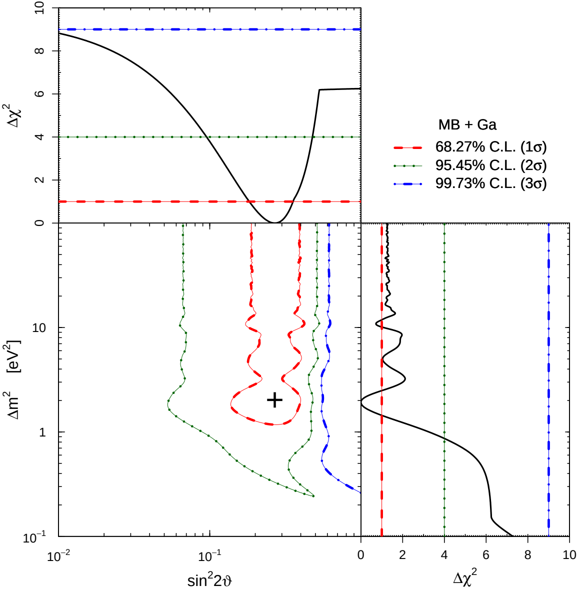
$\sin^2 2\vartheta = 0.32$

$\Delta m^2 = 1.84 \, \text{eV}^2$

- Note similar best-fit values of $\sin^2 2\vartheta$ and Δm^2
- Gallium best fit: $\sin^2 2\vartheta = 0.27$ and $\Delta m^2 = 2.09\,\mathrm{eV}^2$
- MiniBooNE best fit: $\sin^2 2\vartheta = 0.32$ and $\Delta m^2 = 1.84\,\mathrm{eV}^2$
- Parameter Goodness of Fit of combined analysis:

$$\Delta\chi^2_{\text{min}} = 0.14 \qquad \text{NDF} = 2 \qquad \text{GoF} = 93\%$$

MiniBooNE + Gallium



$\chi^2_{\text{min}} = 2.3 + 9.2$

$\text{NdF} = 20$

$\text{GoF} = 93\%$

$\sin^2 2\vartheta = 0.27$

$\Delta m^2 = 1.92\,\text{eV}^2$

[Giunti, Laveder, 2010, arXiv:1005.4599]