Short-Baseline Neutrino Oscillations

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Neutrino Unbound: http://www.nu.to.infn.it

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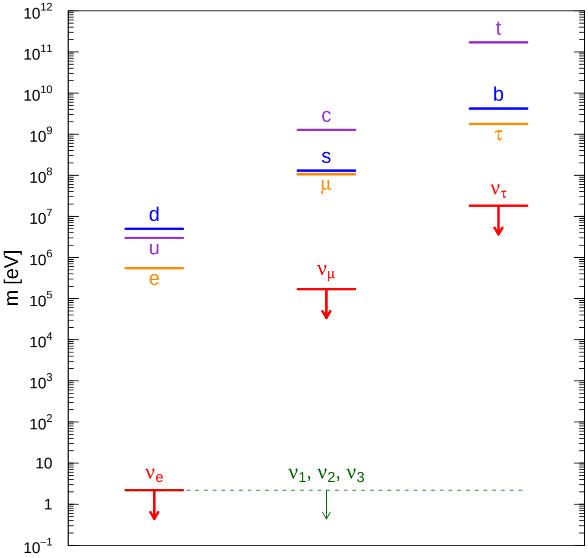
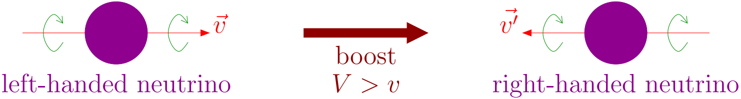
Collaboration with Marco Laveder (Padova University)

Fermion Mass Spectrum



Standard Model: Massless Neutrinos



Standard Model: $\nu_L, \bar{\nu}_R \implies$ no Dirac mass term

$$\mathcal{L}^{\mathrm{D}} \sim m^{\mathrm{D}} \left(\nu_L \nu_R + \bar{\nu}_L \bar{\nu}_R \right) \qquad \text{(no } \nu_R, \, \bar{\nu}_L\text{)}$$

Majorana Neutrino: $\bar{\nu} = \nu \implies \bar{\nu}_R = \nu_R \implies$ Majorana mass term

$$\mathcal{L}^{\mathrm{M}} \sim m^{\mathrm{M}} \nu_L \bar{\nu}_R$$

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

(no Higgs triplet)

Extension of the SM: Massive Neutrinos

Standard Model can be extended with ν_R and corresponding $\bar{\nu}_L$

Dirac neutrino mass term $\mathcal{L}^{\mathrm{D}} \sim m^{\mathrm{D}} \left(\nu_L \nu_R + \bar{\nu}_L \bar{\nu}_R \right) \Rightarrow m^{\mathrm{D}} \lesssim 100\,\mathrm{GeV}$

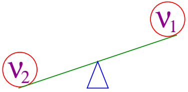
surprise: Majorana neutrino mass for ν_R and $\bar{\nu}_L$ is allowed! $\quad \mathcal{L}^{\mathrm{M}}_R \sim m^{\mathrm{M}}_R \bar{\nu}_L \nu_R$

total neutrino mass term $\quad \mathcal{L}^{\mathrm{D+M}} \sim \begin{pmatrix} \nu_L & \bar{\nu}_L \end{pmatrix} \begin{pmatrix} 0 & m^{\mathrm{D}} \\ m^{\mathrm{D}} & m^{\mathrm{M}}_R \end{pmatrix} \begin{pmatrix} \bar{\nu}_R \\ \nu_R \end{pmatrix}$

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 $\begin{pmatrix} 0 & m^{\mathrm{D}} \\ m^{\mathrm{D}} & m^{\mathrm{M}}_R \end{pmatrix} \quad \Rightarrow \quad m_1 \simeq \dfrac{(m^{\mathrm{D}})^2}{m^{\mathrm{M}}_R}, \quad m_2 \simeq m^{\mathrm{M}}_R$



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
$(\bar{\nu}_e\,,\,e^+)$	-1	0	0
$(\bar{\nu}_\mu\,,\,\mu^+)$	0	-1	0
$(\bar{\nu}_\tau\,,\,\tau^+)$	0	0	-1

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

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

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 $\sim m^{\mathrm{M}} \nu_L \bar{\nu}_R \to \begin{pmatrix} \nu_{eL} & \nu_{\mu L} & \nu_{\tau L} \end{pmatrix} \begin{pmatrix} m^{\mathrm{M}}_{ee} & m^{\mathrm{M}}_{e\mu} & m^{\mathrm{M}}_{e\tau} \\ m^{\mathrm{M}}_{\mu e} & m^{\mathrm{M}}_{\mu\mu} & m^{\mathrm{M}}_{\mu\tau} \\ m^{\mathrm{M}}_{\tau e} & m^{\mathrm{M}}_{\tau\mu} & m^{\mathrm{M}}_{\tau\tau} \end{pmatrix} \begin{pmatrix} \bar{\nu}_{eR} \\ \bar{\nu}_{\mu R} \\ \bar{\nu}_{\tau R} \end{pmatrix}$

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

Neutrino Mixing

$$\mathcal{L}_{\text{mass}} \sim \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{\mu e} & m_{\mu\mu} & m_{\mu\tau} \\ m_{\tau e} & m_{\tau\mu} & m_{\tau\tau} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

diagonalization of mass matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

$$\mathcal{L}_{\text{mass}} \sim \begin{pmatrix} \nu_1 & \nu_2 & \nu_3 \end{pmatrix} \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \sum_{k=1}^{3} m_k \nu_k \nu_k$$

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

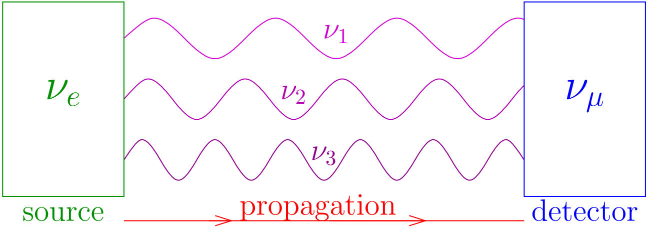
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector

- A Flavor Neutrino is a superposition of Massive Neutrinos

$$
\begin{aligned}
|\nu_e\rangle &= U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle \\
|\nu_\mu\rangle &= U_{\mu 1}\,|\nu_1\rangle + U_{\mu 2}\,|\nu_2\rangle + U_{\mu 3}\,|\nu_3\rangle \\
|\nu_\tau\rangle &= U_{\tau 1}\,|\nu_1\rangle + U_{\tau 2}\,|\nu_2\rangle + U_{\tau 3}\,|\nu_3\rangle
\end{aligned}
$$

- 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

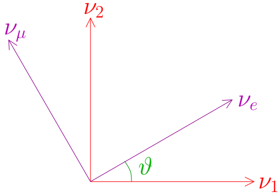
Neutrino Oscillations are Flavor Transitions

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

$$\bar{\nu}_e \to \bar{\nu}_\mu \qquad \bar{\nu}_e \to \bar{\nu}_\tau \qquad \bar{\nu}_\mu \to \bar{\nu}_e \qquad \bar{\nu}_\mu \to \bar{\nu}_\tau$$

Two-Neutrino Mixing and Oscillations

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



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

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

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

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

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

Solar and Atmospheric 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)

$\to$ $\Delta m^2_{\text{SOL}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$, $\sin^2\vartheta_{\text{SOL}} \simeq 0.30$

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

Accelerator
ν_μ disappearance

Kamiokande
IMB
Super-Kamiokande
MACRO
Soudan-2

(K2K & MINOS)

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

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

Large mixings: $\vartheta_{\text{ATM}} \simeq 45^\circ$, $\vartheta_{\text{SOL}} \simeq 33^\circ$

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

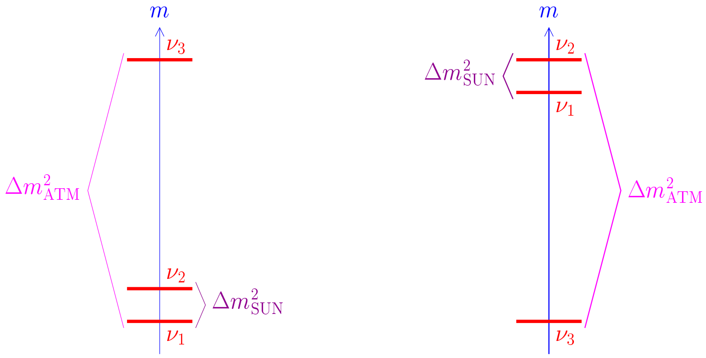
three massive fields: ν_1, ν_2, ν_3

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

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

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

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

Mixing Matrix

$$\begin{array}{c} \text{SOL} \rightarrow \\ U = \end{array} \begin{pmatrix} \boxed{U_{e1} \quad U_{e2}} & \boxed{U_{e3}} \\ U_{\mu 1} \quad U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} \quad U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

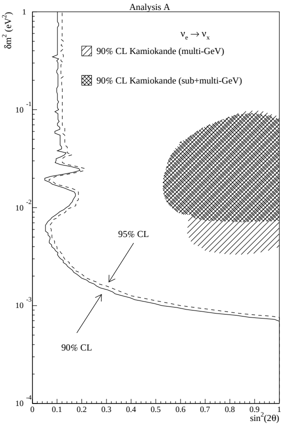
$\uparrow$ ATM & LBL

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

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

$$\Downarrow$$

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



[CHOOZ, PLB 466 (1999) 415]

[Palo Verde, PRD 64 (2001) 112001]

SOLAR AND ATMOSPHERIC ν OSCILLATIONS ARE PRACTICALLY DECOUPLED!

$$|U_{e1}|^2 \simeq \cos^2\vartheta_{\text{SOL}} \qquad |U_{e2}|^2 \simeq \sin^2\vartheta_{\text{SOL}}$$

$$|U_{\mu 3}|^2 \simeq \sin^2\vartheta_{\text{ATM}} \qquad |U_{\tau 3}|^2 \simeq \cos^2\vartheta_{\text{ATM}}$$

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

$\vartheta_{23} \simeq \vartheta_{\text{ATM}}$ $\quad$ $\vartheta_{12} \simeq \vartheta_{\text{SOL}}$ $\quad$ $\beta\beta_{0\nu}$

$$\Delta m^2_{21} = \left(7.65^{+0.23}_{-0.20}\right) \times 10^{-5}\,\text{eV}^2 \qquad |\Delta m^2_{31}| = \left(2.40^{+0.12}_{-0.11}\right) \times 10^{-3}\,\text{eV}^2$$

$$\sin^2\vartheta_{12} = 0.304^{+0.022}_{-0.016} \qquad \sin^2\vartheta_{23} = 0.50^{+0.07}_{-0.06}$$

$$\sin^2\vartheta_{13} < 0.035 \quad (90\%\ \text{C.L.})$$

[Schwetz, Tortola, Valle, arXiv:0808.2016v3, 11 Feb 2010]

$$U \simeq \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Tri-Bimaximal Mixing

[Harrison, Perkins, Scott, PLB 530 (2002) 167]

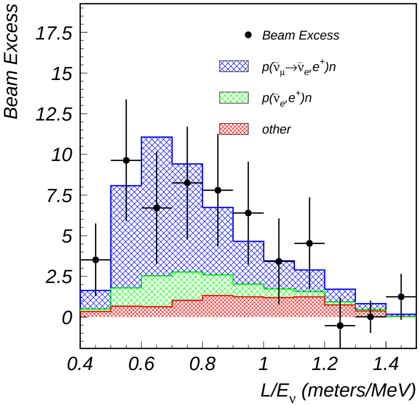
Current Research

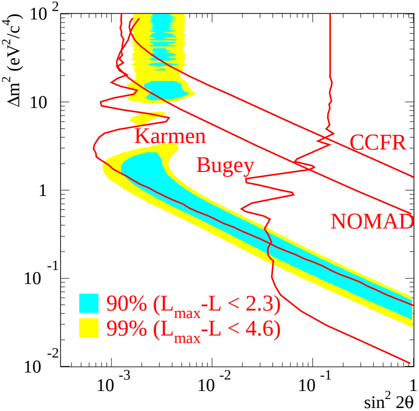
measure $\vartheta_{13} \neq 0 \Longrightarrow$ CP violation, matter effects, mass hierarchy

LSND

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

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





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

- New Short-BaseLine Oscillations: $\frac{L}{E} \lesssim 1 \frac{\text{m}}{\text{MeV}} \implies \Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2$

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

Mass Basis: $\nu_1 \quad \nu_2 \quad \nu_3 \quad \nu_4$

Flavor Basis: $\nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_s$

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

- CP violation in SBL: at least 5-ν Mixing

Mass Basis: $\nu_1 \quad \nu_2 \quad \nu_3 \quad \nu_4 \quad \nu_5$

Flavor Basis: $\nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_{s1} \quad \nu_{s2}$

$$\Delta m^2_{\text{SBL1}} = \Delta m^2_{41} \quad < \quad \Delta m^2_{\text{SBL2}} = \Delta m^2_{51}$$

Sterile Neutrinos

- Light anti-ν_R are called sterile neutrinos

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

- Sterile means no standard model interactions
- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos
  - Indirect evidence through combined fit of data
- Extremely interesting and powerful window on new physics beyond the Standard Model

How many Sterile Neutrinos?

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

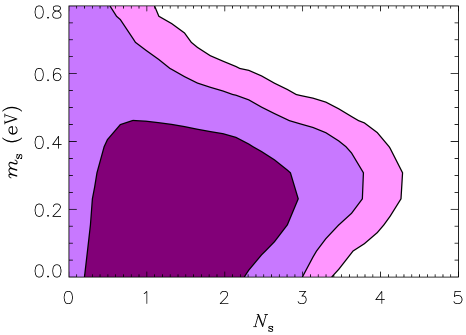
mixing $\Rightarrow \quad \nu_{\alpha L} = \sum_{k=1}^{N} U_{\alpha k} \nu_{kL} \qquad \alpha = e, \mu, \tau$

$N \geq 3$
no upper limit!

Mass Basis:	ν_1	ν_2	ν_3	ν_4	ν_5	$\cdots$
Flavor Basis:	ν_e	ν_μ	ν_τ	ν_{s_1}	ν_{s_2}	$\cdots$
		ACTIVE			STERILE	

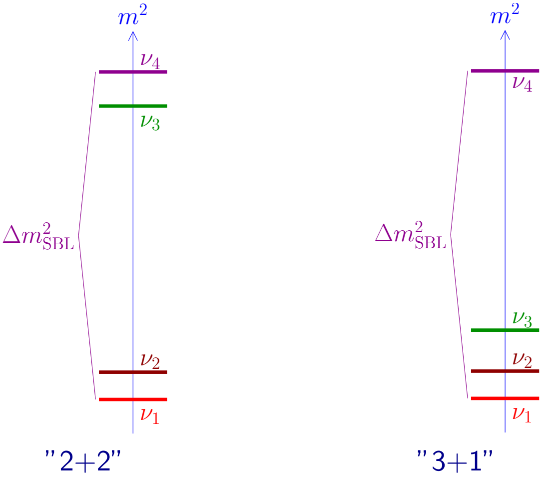
Cosmology

- CMB and LSS in ΛCDM: [Hamann, Hannestad, Raffelt, Tamborra, Wong, arXiv:1006.5276]

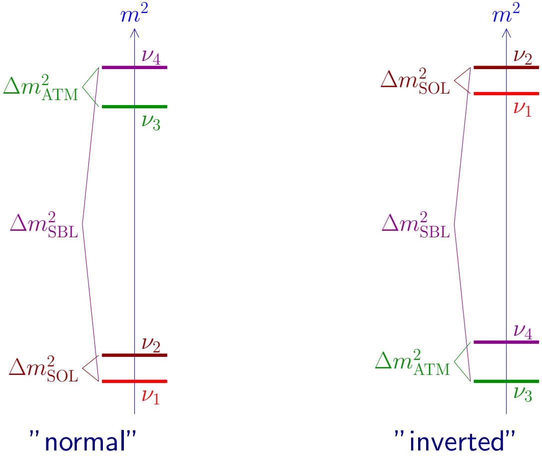


- BBN: $N_s = 0.68^{+0.80}_{-0.70}$ [Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440]

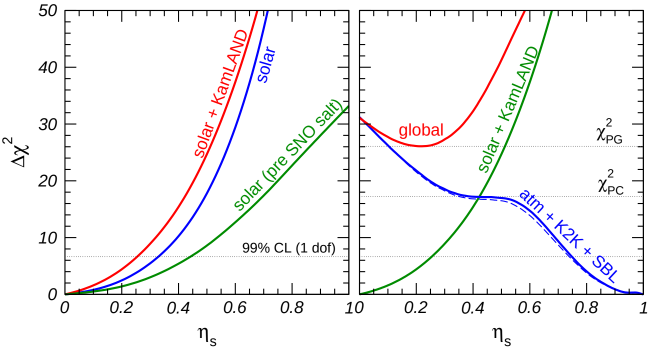
Four-Neutrino Schemes: 2+2 and 3+1



2+2 Four-Neutrino Schemes



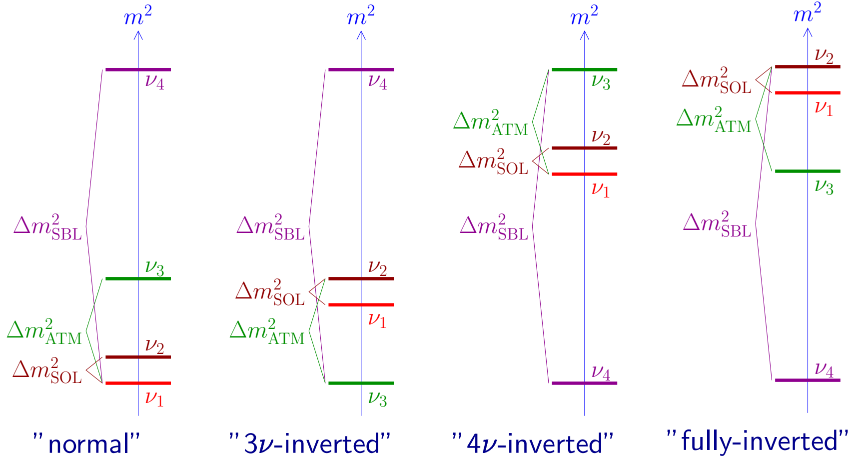
2+2 Schemes are strongly disfavored by solar and atmospheric data



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

$$\eta_s = |U_{s1}|^2 + |U_{s2}|^2 \qquad 99\%\ \mathrm{CL:} \begin{cases} \eta_s < 0.25 & \text{(solar + KamLAND)} \\ \eta_s > 0.75 & \text{(atmospheric + K2K)} \end{cases}$$

3+1 Four-Neutrino Schemes



Perturbation of 3-ν Mixing

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

SBL Oscillation Probabilities in 3+1 Schemes

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

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

No CP Violation!

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

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

Perturbation of 3ν Mixing

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

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

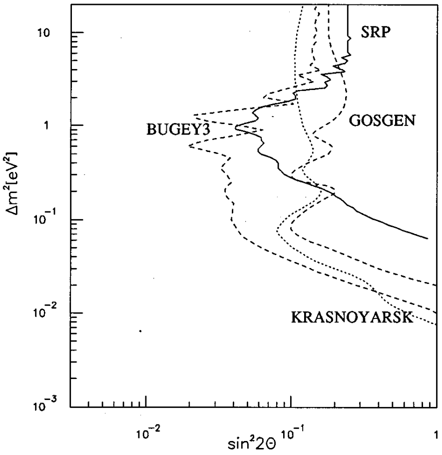
SBL

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

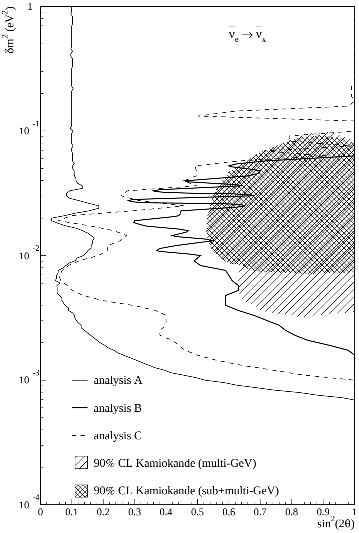
$$\Downarrow$$

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

$\bar{\nu}_e$ Disappearance

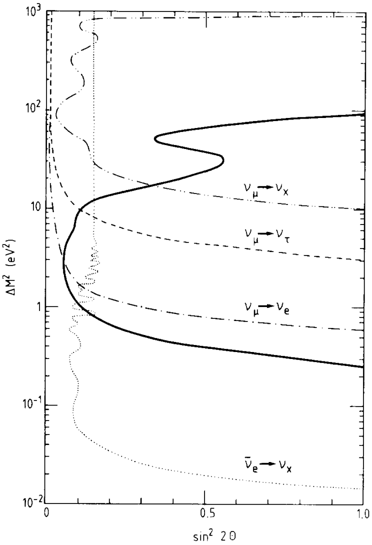


[Savannah River (SRP), PRD 53 (1996) 6054]

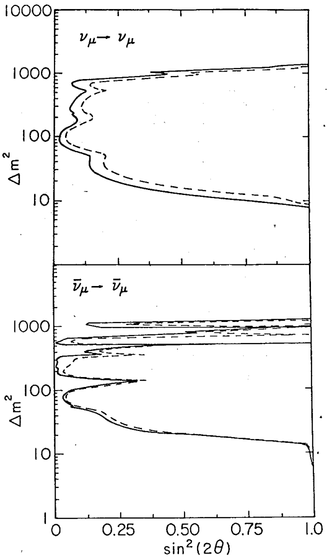


[CHOOZ, Eur. Phys. J. C27 (2003) 331, hep-ex/0301017]

ν_μ and $\bar{\nu}_\mu$ Disappearance



[CDHSW, PLB 134 (1984) 281]



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

- 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:

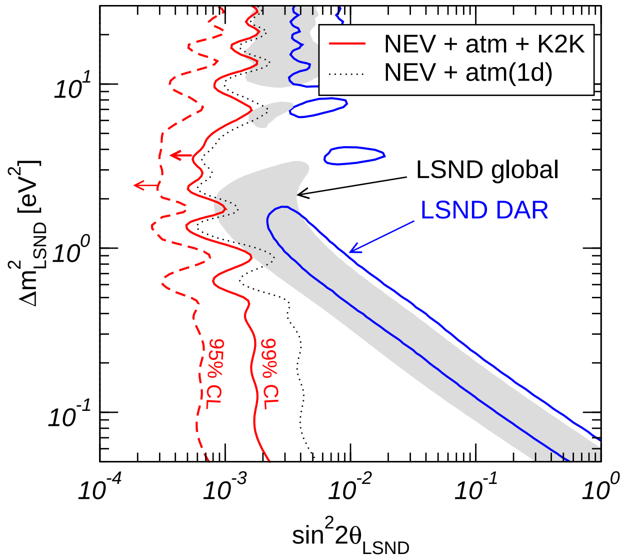
$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 \left(1 - |U_{\mu4}|^2\right) \simeq 4|U_{\mu4}|^2$$

- $\nu_\mu \to \nu_e$ 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 $\sin^2 2\vartheta_{e\mu}$

$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ in 3+1 Schemes

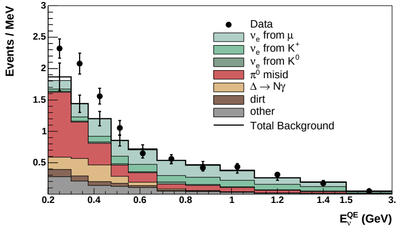


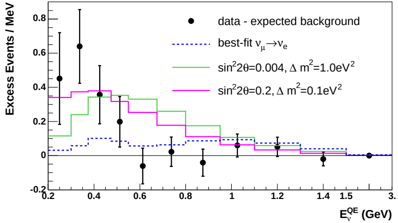
[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

MiniBooNE Neutrinos

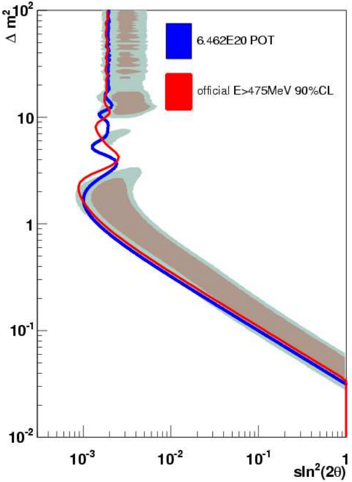
[PRL 98 (2007) 231801; PRL 102 (2009) 101802]

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





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



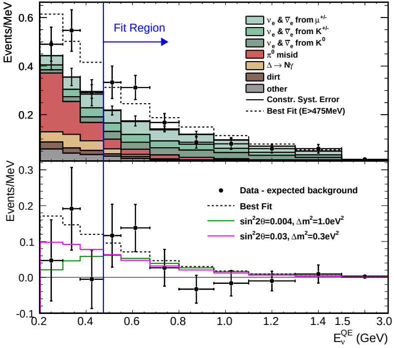
[Djurcic, arXiv:0901.1648]

Low-Energy Anomaly!

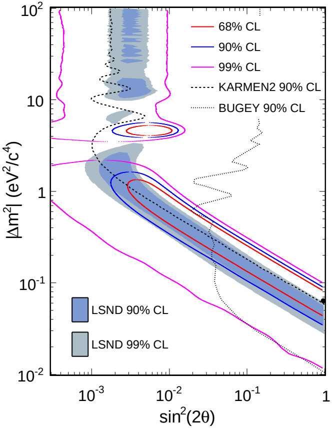
MiniBooNE Antineutrinos

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

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

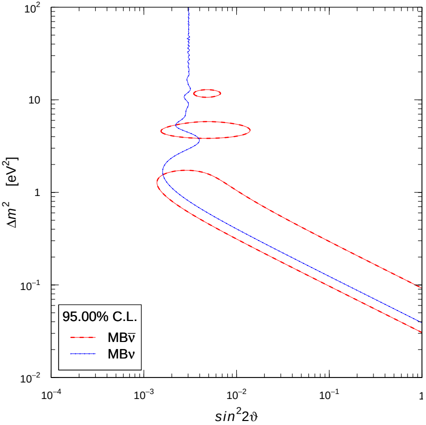


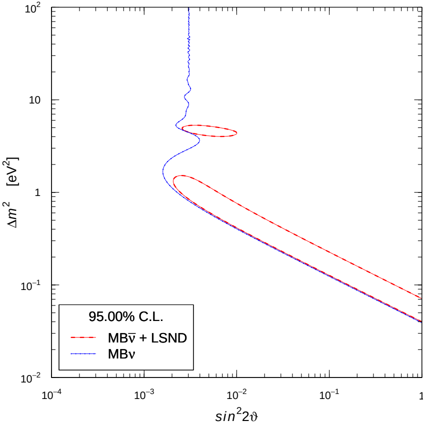
[MiniBooNE, PRL 105 (2010) 181801, arXiv:1007.1150]



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

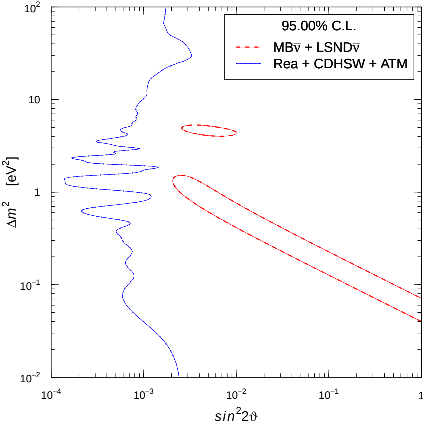
Similar L/E but different L and E $\Longrightarrow$ Oscillations!



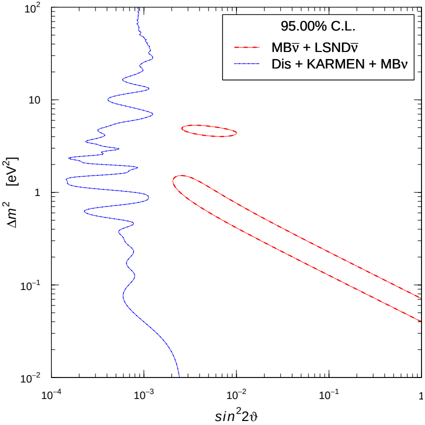


PGoF = 2.4% PGoF = 0.24%

- 3+1 Four-Neutrino Schemes Strong tension between LSND + MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ and MiniBooNE $\nu_\mu \to \nu_e \Longrightarrow$ CP Violation?
- 3+2 $\Longrightarrow$ CP Violation OK [Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004, hep-ph/0305255; Maltoni, Schwetz, PRD 76, 093005 (2007), arXiv:0705.0107; Karagiorgi et al, PRD 80 (2009) 073001, arXiv:0906.1997]
- 3+1 + NSI $\Longrightarrow$ CP Violation OK [Akhmedov, Schwetz, JHEP 10 (2010) 115, arXiv:1007.4171]



$\text{PGoF} = 0.074\%$



$\text{PGoF} = 0.0048\%$

- Strong tension between LSND + MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\bar{\nu}_e$ (Bugey) + $\overset{(-)}{\nu}_\mu$ (CDHSW+ATM) disappearance limits + KARMEN $\bar{\nu}_\mu \to \bar{\nu}_e$ + and MiniBooNE $\nu_\mu \to \nu_e$
- CPT Violation?

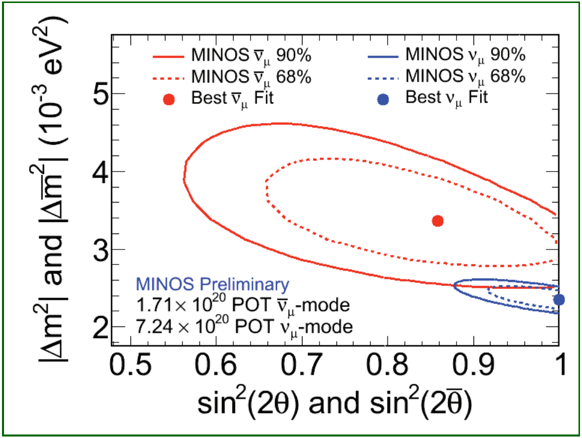
[Barger, Marfatia, Whisnant, PLB 576 (2003) 303]

[Giunti, Laveder, PRD 82 (2010) 093016, arXiv:1010.1395; arXiv:1012.0267]

MINOS Hint of CPT Violation

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

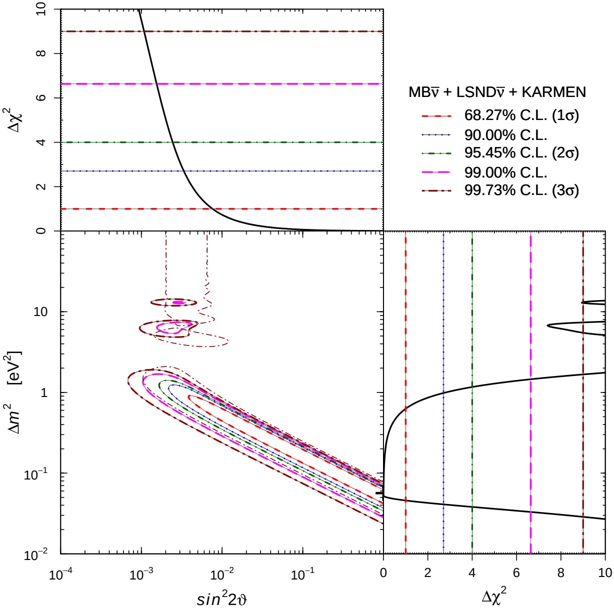
Near Detector at 1.04 km $\qquad$ Far Detector at 734 km



[MINOS, Neutrino 2010, 14 June 2010]

Phenomenological Approach: Consider $\bar{\nu}$'s Only

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



$\chi^2_{\text{min}} = 29.8$

$\text{NdF} = 26$

$\text{GoF} = 28\%$

$\sin^2 2\vartheta = 1.00$

$\Delta m^2 = 0.052\,\text{eV}^2$

Parameter Goodness-of-Fit

$\Delta\chi^2_{\text{min}} = 5.9$

$\text{NdF} = 4$

$\text{GoF} = 21\%$

[Giunti, Laveder, PRD 82 (2010) 093016, arXiv:1010.1395]

Conservation of Probability

$$\sum_{\alpha} P_{\bar{\nu}_\alpha \to \bar{\nu}_e} = 1$$

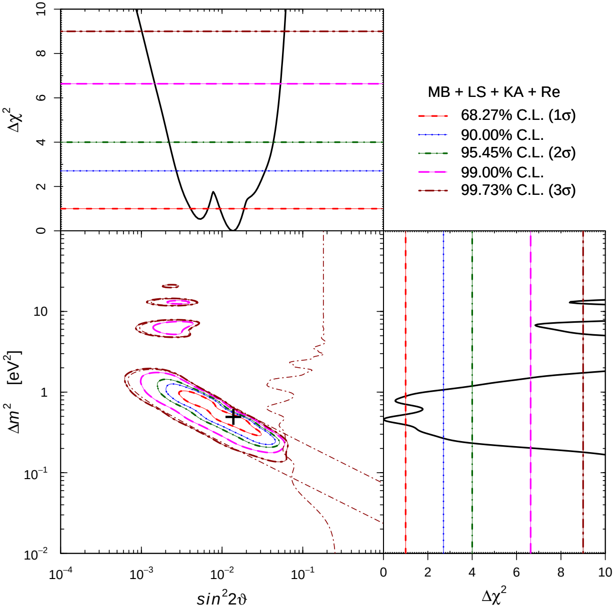
$$P_{\bar{\nu}_e \to \bar{\nu}_e} + P_{\bar{\nu}_\mu \to \bar{\nu}_e} + P_{\bar{\nu}_\tau \to \bar{\nu}_e} + P_{\bar{\nu}_s \to \bar{\nu}_e} = 1$$

$$P_{\bar{\nu}_\mu \to \bar{\nu}_e} = 1 - P_{\bar{\nu}_e \to \bar{\nu}_e} - P_{\bar{\nu}_\tau \to \bar{\nu}_e} - P_{\bar{\nu}_s \to \bar{\nu}_e}$$

$$\boxed{P_{\bar{\nu}_\mu \to \bar{\nu}_e} \leq 1 - P_{\bar{\nu}_e \to \bar{\nu}_e}}$$

Reactor $\bar{\nu}_e$ disappearance bound is unavoidable!

$\bar{\nu}_\mu \to \bar{\nu}_e$ and $\bar{\nu}_e \to \bar{\nu}_e$



$\chi^2_{\text{min}} = 81.4$

$\text{NdF} = 82$

$\text{GoF} = 50\%$

$\sin^2 2\vartheta = 0.014$

$\Delta m^2 = 0.46\,\text{eV}^2$

Parameter Goodness-of-Fit

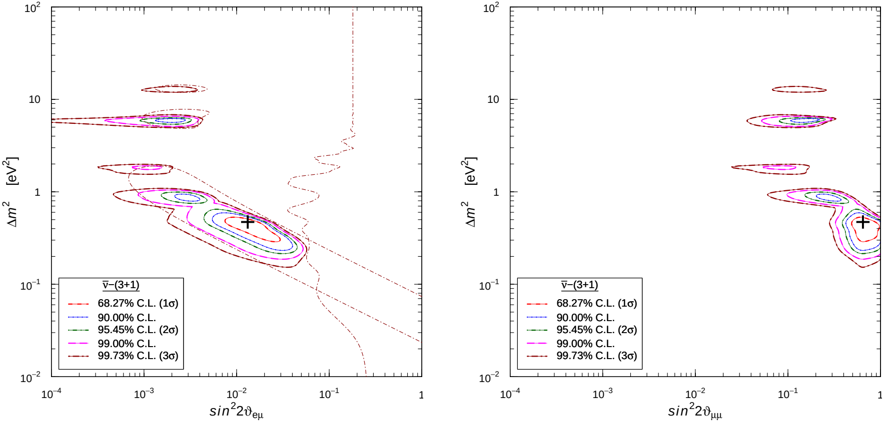
$\Delta\chi^2_{\text{min}} = 3.0$

$\text{NdF} = 2$

$\text{GoF} = 22\%$

[Giunti, Laveder, PRD 82 (2010) 093016, arXiv:1010.1395]

Antineutrino Oscillations in 3+1 Schemes



$$\chi^2_{\text{min}} = 82.0 \qquad \text{NdF} = 82 \qquad \text{GoF} = 48\%$$

$$\Delta m^2 = 0.44\,\text{eV}^2 \quad \sin^2 2\vartheta_{e\mu} = 0.013 \quad \sin^2 2\vartheta_{ee} = 0.016 \quad \sin^2 2\vartheta_{\mu\mu} = 0.65$$

Prediction: large SBL $\bar{\nu}_\mu$ disappearance at $0.1 \lesssim \Delta m^2 \lesssim 1\,\text{eV}^2$

[Giunti, Laveder, arXiv:1012.0267]

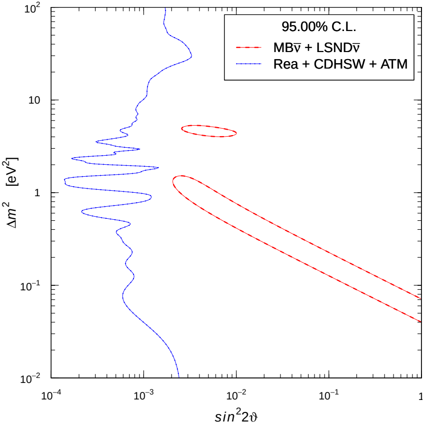
New Calculation of Reactor $\bar{\nu}_e$ Flux

- Th. A. Mueller, D. Lhuillier, M. Fallot, A. Letourneau, S. Cormon, M. Fechner, L. Giot, T. Lasserre, J. Martino, G. Mention, A. Porta, F. Yermia, Improved Predictions of Reactor Antineutrino Spectra, arXiv:1101.2663 (Thu, 13 Jan 2011)
  - "new reference antineutrino spectra for 235U, 239Pu and 241Pu"
  - "the normalization is shifted by about $+3\%$ on average"

- G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller, D. Lhuillier, M. Cribier, A. Letourneau, The Reactor Antineutrino Anomaly, arXiv:1101.2755 (Fri, 14 Jan 2011)
  - "synthesis of published experiments at reactor-detector distances $< 100\,\mathrm{m}$ leads to a ratio of observed event rate to predicted rate of 0.979 (0.029)"
  - "this ratio shifts to 0.937 (0.027), leading to a deviation from unity at 98.4% C.L. which we call the reactor antineutrino anomaly"

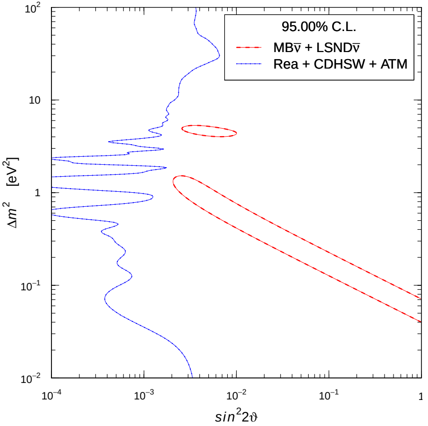
- New reactor neutrino flux has several implications: fit of solar and KamLAND data, determination of ϑ_{13}, short-baseline $\bar{\nu}_e$ disappearance, ...

Standard Reactor $\bar{\nu}_e$ Fluxes



PGoF $= 0.074\%$

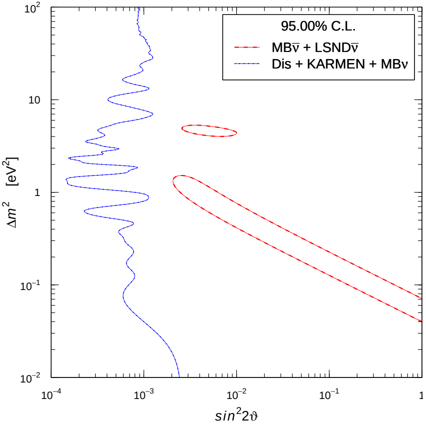
New Reactor $\bar{\nu}_e$ Fluxes



PGoF $= 0.27\%$

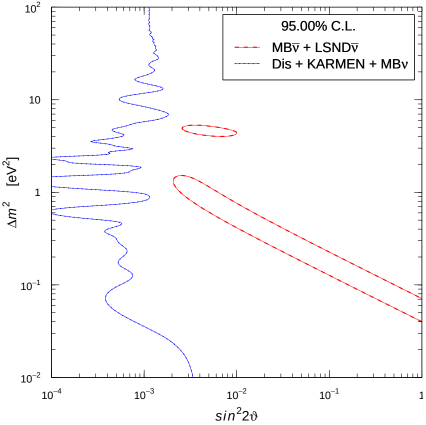
- New reactor neutrino flux evaluation decreases the tension between LSND + MiniBooNE and disappearance limits

Standard Reactor $\bar{\nu}_e$ Fluxes



PGoF = 0.0048%

New Reactor $\bar{\nu}_e$ Fluxes



PGoF = 0.0064%

- Strong tension between LSND + MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\bar{\nu}_e$ (Bugey) + $\overset{(-)}{\nu}_\mu$ (CDHSW+ATM) disappearance limits + KARMEN $\bar{\nu}_\mu \to \bar{\nu}_e$ + and MiniBooNE $\nu_\mu \to \nu_e$ remains

Gallium Anomaly

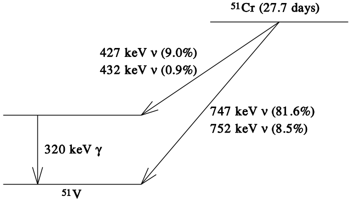
Gallium Radioactive Source Experiments

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

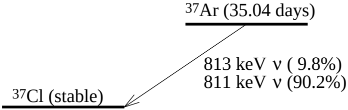
Detection Process: $\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$

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

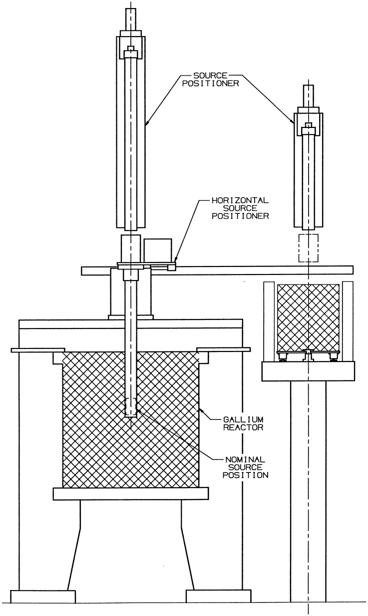
	${}^{51}\mathrm{Cr}$				${}^{37}\mathrm{Ar}$	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098



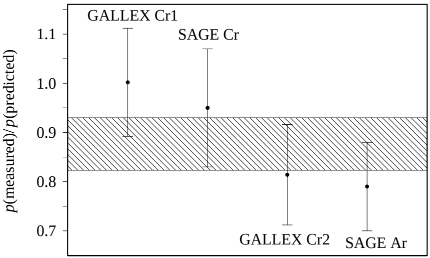
[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]



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



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



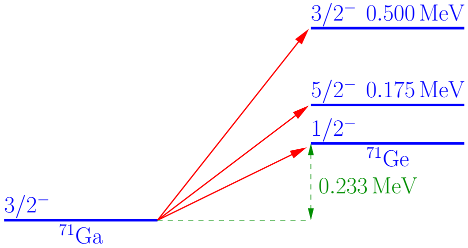
[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

$$\boxed{R_{\text{Ga}} = 0.86 \pm 0.05}$$

- Deficit could be due to overestimate of

$$\sigma(\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-)$$

- Calculation: Bahcall, PRC 56 (1997) 3391, hep-ph/9710491



- $\sigma_{\text{G.S.}}$ related to measured $\sigma(e^- + {}^{71}\text{Ge} \to {}^{71}\text{Ga} + \nu_e)$:

$$\sigma_{\text{G.S.}}({}^{51}\text{Cr}) = 55.3 \times 10^{-46}\,\text{cm}^2\,(1 \pm 0.004)_{3\sigma}$$

- $\sigma({}^{51}\text{Cr}) = \sigma_{\text{G.S.}}({}^{51}\text{Cr}) \left(1 + 0.669\,\frac{\text{BGT}_{175\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} + 0.220\,\frac{\text{BGT}_{500\,\text{keV}}}{\text{BGT}_{\text{G.S.}}}\right)$

- Contribution of Excited States only 5%!

- Bahcall: [Bahcall, PRC 56 (1997) 3391, hep-ph/9710491]

  from $p + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + n$ measurements [Krofcheck et al., PRL 55 (1985) 1051]

$$\frac{\text{BGT}_{175\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \Rightarrow \frac{\text{BGT}_{175\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = \frac{0.056}{2} \qquad \frac{\text{BGT}_{500\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146$$

3σ lower limit: $\dfrac{\text{BGT}_{175\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = \dfrac{\text{BGT}_{500\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = 0$

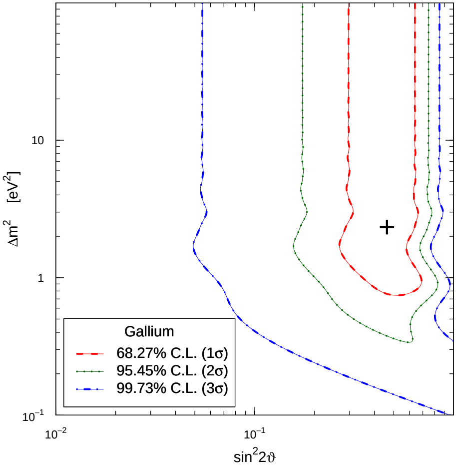
3σ upper limit: $\dfrac{\text{BGT}_{175\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \times 2 \qquad \dfrac{\text{BGT}_{500\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146 \times 2$

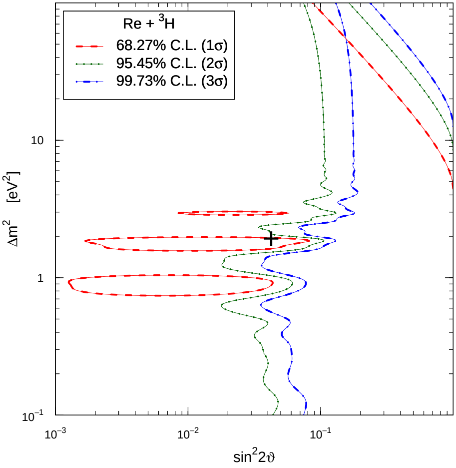
$$\sigma({}^{51}\text{Cr}) = 58.1 \times 10^{-46}\,\text{cm}^2 \left(1^{+0.036}_{-0.028}\right)_{1\sigma} \Longrightarrow \boxed{R_{\text{Ga}} = 0.86 \pm 0.05}$$

- Haxton: [Hata, Haxton, PLB 353 (1995) 422, nucl-th/9503017; Haxton, PLB 431 (1998) 110, nucl-th/9804011]

  "a sophisticated shell model calculation is performed ... for the transition to the first excited state in ^{71}Ge. The calculation predicts destructive interference between the (p, n) spin and spin-tensor matrix elements."

$$\sigma({}^{51}\text{Cr}) = 63.9 \times 10^{-46}\,\text{cm}^2\,(1 \pm 0.106)_{1\sigma} \Longrightarrow \boxed{R_{\text{Ga}} = 0.76^{+0.09}_{-0.08}}$$





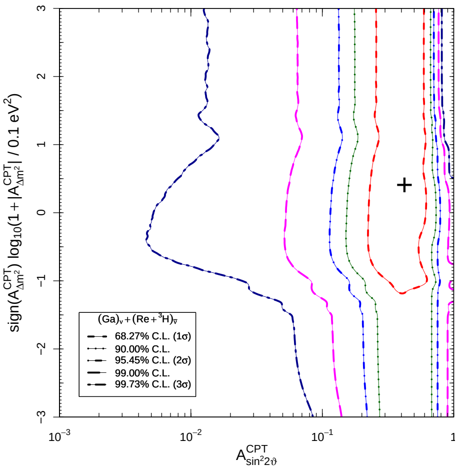
[Giunti, Laveder, arXiv:1006.3244]

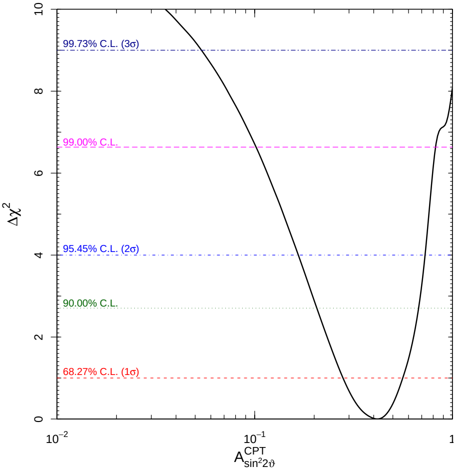
[Giunti, Laveder, PRD 82 (2010) 053005, arXiv:1005.4599]

$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2$ is OK

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

Parameter Goodness-Of-Fit: $\Delta\chi^2_{\text{min}} = 12.1\,,\ \text{NDF} = 2\,,\ \text{GoF} = 0.2\%$





[Giunti, Laveder, PRD 82 (2010) 113009, arXiv:1008.4750]

$$A^{CPT}_{\sin^2 2\vartheta} = \sin^2 2\vartheta_\nu - \sin^2 2\vartheta_{\bar\nu} \qquad (A^{CPT}_{\sin^2 2\vartheta})_{bf} = 0.42$$

$$A^{CPT}_{\Delta m^2} = \Delta m^2_\nu - \Delta m^2_{\bar\nu} \qquad (A^{CPT}_{\Delta m^2})_{bf} = 0.37\,\text{eV}^2$$

$$A^{CPT}_{\sin^2 2\vartheta} > 0.055 \text{ at } 3\sigma \qquad A^{CPT}_{\sin^2 2\vartheta} > 0 \text{ at } 3.5\sigma.$$

Future

- New Gallium source experiments: ν_e disappearance [Gavrin et al, arXiv:1006.2103]

- CPT test: ν_e and $\bar{\nu}_e$ disappearance

- Beta-Beam experiments: [Antusch, Fernandez-Martinez, PLB 665 (2008) 190, arXiv:0804.2820]

$$N(A,Z) \to N(A,Z+1) + e^- + \bar{\nu}_e \qquad (\beta^-)$$

$$N(A,Z) \to N(A,Z-1) + e^+ + \nu_e \qquad (\beta^+)$$

- Neutrino Factory experiments: [Giunti, Laveder, Winter, PRD 80 (2009) 073005, arXiv:0907.5487]

$$\mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e$$

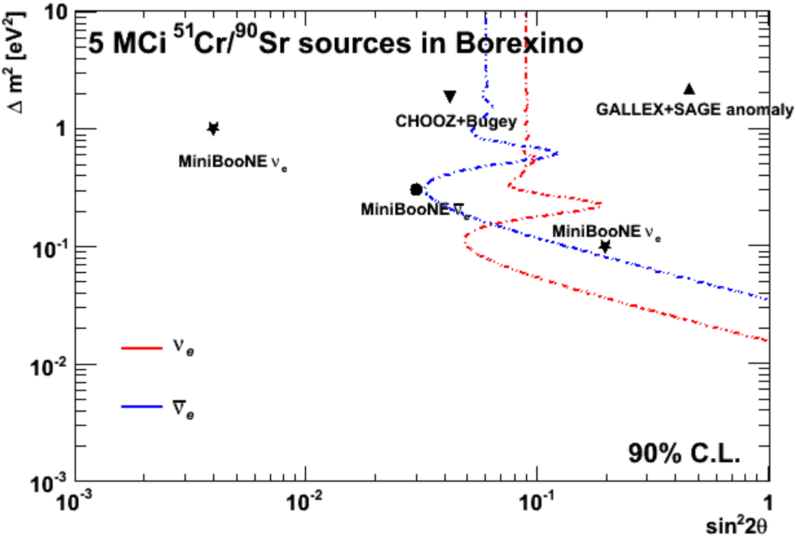
$$\mu^- \to \nu_\mu + e^- + \bar{\nu}_e$$

- New ν_e and $\bar{\nu}_e$ radioactive source experiments with low-threshold neutrino elastic scattering detectors.
- LENS (Low Energy Neutrino Spectroscopy): [Agarwalla, Raghavan, arXiv:1011.4509]

$$\nu_e + {}^{115}\text{In} \to {}^{115}\text{Sn} + e^- + 2\gamma \qquad E_{\text{th}} = 0.1\,\text{MeV}$$

$$\bar{\nu}_e + p \to n + e^+ \qquad E_{\text{th}} = 1.8\,\text{MeV}$$

- Borexino: [Ianni, Montanino, Scioscia, EPJC 8 (1999) 609, arXiv:hep-ex/9901012]



[A. Ianni, Private Communication]

Conclusions

- Suggestive 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 ν_μ disappearance limits
  - Gallium Anomaly (ν_e disappearance) vs Reactor ($\bar{\nu}_e$ disappearance)
- CPT-invariant 3+1 Four-Neutrino Mixing is strongly disfavored
- CPT-violating 3+1 Mixing $\Longrightarrow$ large SBL $\bar{\nu}_\mu$ disappearance
- 3+2 Five-Neutrino Mixing can explain the CP-violating tension between MiniBooNE $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$
- Work in Progress: global 3+2 fit of SBL data, study of implications of new reactor neutrino flux evaluation, explanation of LSND and MiniBooNE + Gallium Anomaly.
- New short-baseline neutrino oscillation experiments are needed!