Sterile Neutrinos and Short-Baseline Oscillations

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Workshop on Sterile Neutrinos and the Reactor Antineutrino Anomaly

T.U.M, Garching, 8 February 2011

Collaboration with Marco Laveder (Padova University)

Standard Model

- Neutrinos are the only massless fermions
- Neutrinos are the only fermions with only left-handed component ν_L

Extension of the SM: Massive Neutrinos

- Simplest extension: introduce right-handed component ν_R
- Neutrinos become massive
- Dirac mass $m_{\mathrm{D}} \overline{\nu_R} \nu_L$ + Majorana mass $m_{\mathrm{M}} \overline{\nu_R^c} \nu_R$
- It is likely that right-handed neutrinos are connected with new physics beyond the Standard Model

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		

Solar and Atmospheric Neutrino Oscillations

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

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

Reactor
$\bar{\nu}_e$ disappearance

(KamLAND)

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

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

Kamiokande
IMB
Super-Kamiokande
MACRO
Soudan-2

Accelerator
ν_μ disappearance

(K2K & MINOS)

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

Two scales of Δm^2 $\Longleftrightarrow$ Three-Neutrino Mixing

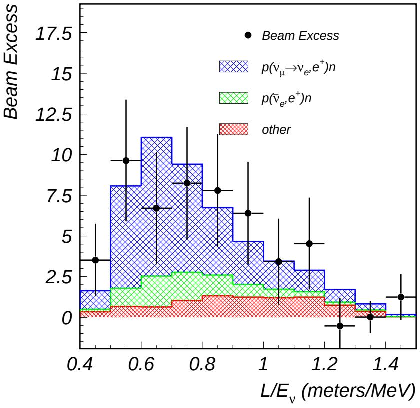
$$\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$$

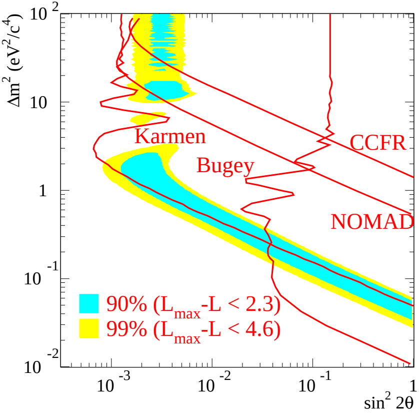
$$\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq 2.4 \times 10^{-3}\,\text{eV}^2$$

LSND

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

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





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

- New Short-BaseLine Oscillations: $\frac{L}{E} \lesssim 1 \, \frac{\text{m}}{\text{MeV}} \quad \Longrightarrow \quad \Delta m^2_{\text{SBL}} \gtrsim 1 \, \text{eV}^2$
- Necessary introduction of at least one new massive neutrino: 4-ν Mixing

$$\text{Mass Basis:} \quad \nu_1 \quad \nu_2 \quad \nu_3 \quad \nu_4$$

$$\text{Flavor Basis:} \quad \nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_s$$

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

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

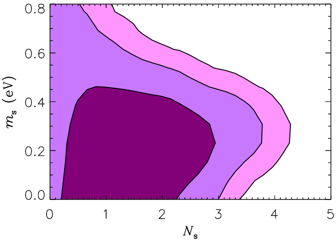
$$\text{Mass Basis:} \quad \nu_1 \quad \nu_2 \quad \nu_3 \quad \nu_4 \quad \nu_5$$

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

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

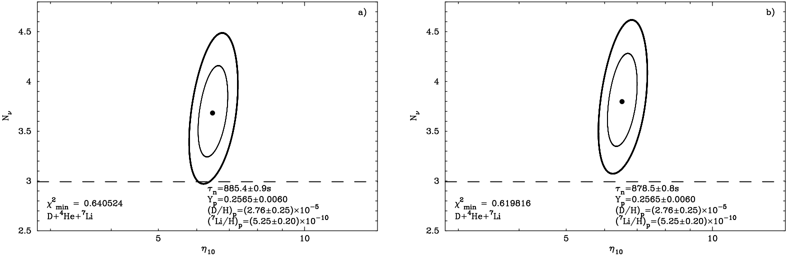
Cosmology

- CMB and LSS in ΛCDM:



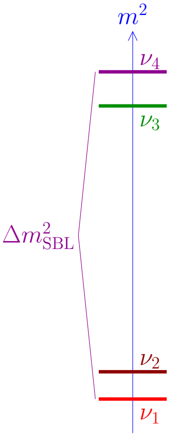
[Hamann, Hannestad, Raffelt, Tamborra, Wong, PRL 105 (2010) 181301, arXiv:1006.5276]

- BBN:

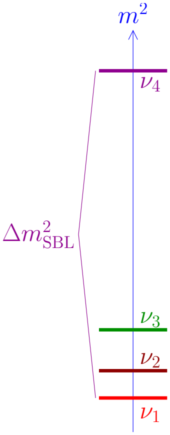


[Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440]

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

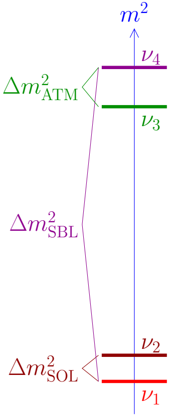


"2+2"

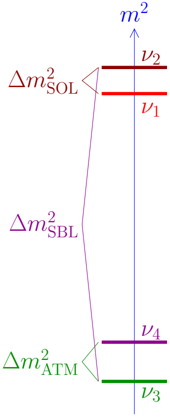


"3+1"

2+2 Four-Neutrino Schemes

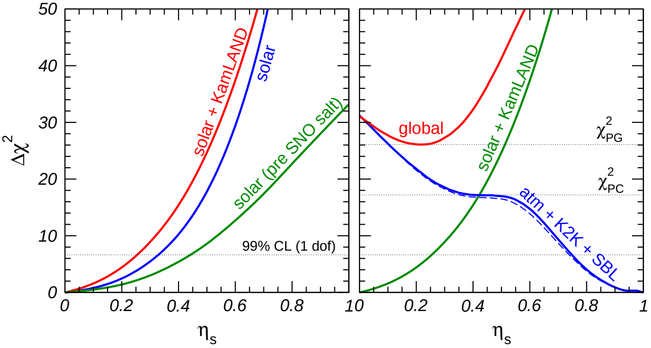


"normal"



"inverted"

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

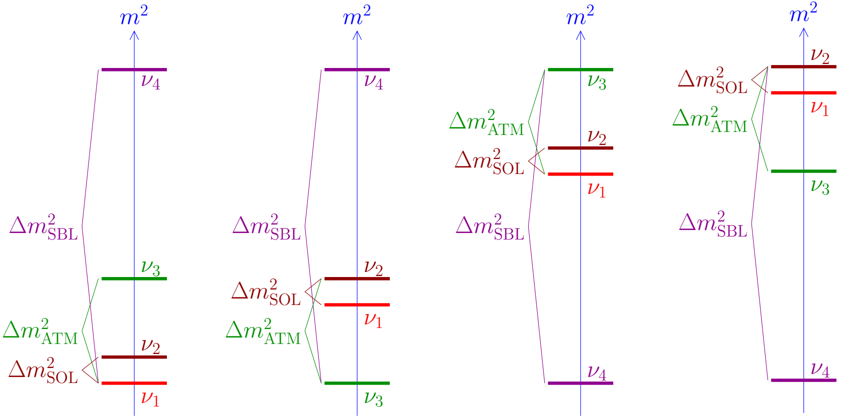


[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

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

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

3+1 Four-Neutrino Schemes



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

Perturbation of 3-ν Mixing

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

SBL Oscillation Probabilities in 3+1 Schemes

$$P_{\nu_\alpha\to\nu_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha4}|^2|U_{\beta4}|^2$$

No CP Violation!

$$P_{\nu_\alpha\to\nu_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha4}|^2\left(1-|U_{\alpha4}|^2\right)$$

Perturbation of 3ν Mixing

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

$$U = \left(\begin{array}{ccc|c|} \cline{4-4} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \\ \cline{4-4} \end{array}\right)$$

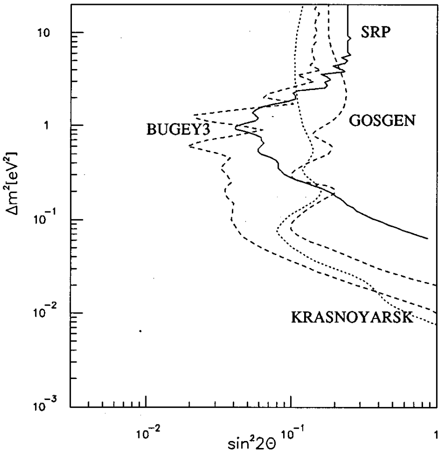
$$\begin{array}{cccc} \phantom{U_{e1}} & \phantom{U_{e2}} & \phantom{U_{e3}} & \uparrow \\ & & & \text{SBL} \end{array}$$

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

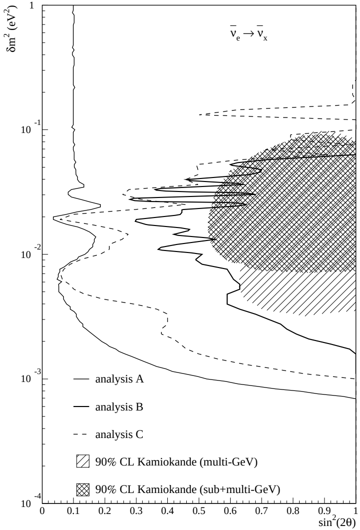
$$\Downarrow$$

$$|U_{\alpha4}|^2 \simeq \frac{\sin^2 2\vartheta_{\alpha\alpha}}{4}$$

$\bar{\nu}_e$ Disappearance

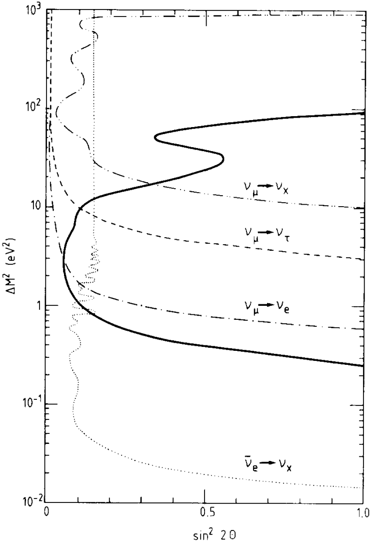


[Savannah River (SRP), PRD 53 (1996) 6054]

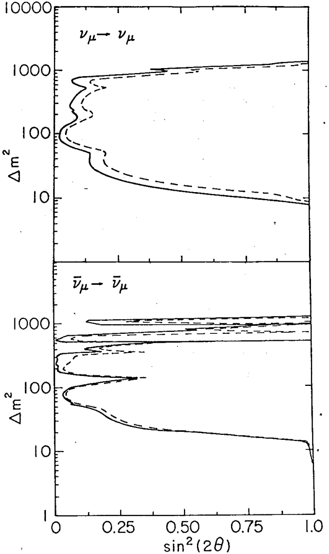


[CHOOZ, Eur. Phys. J. C27 (2003) 331, hep-ex/0301017]

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:

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

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

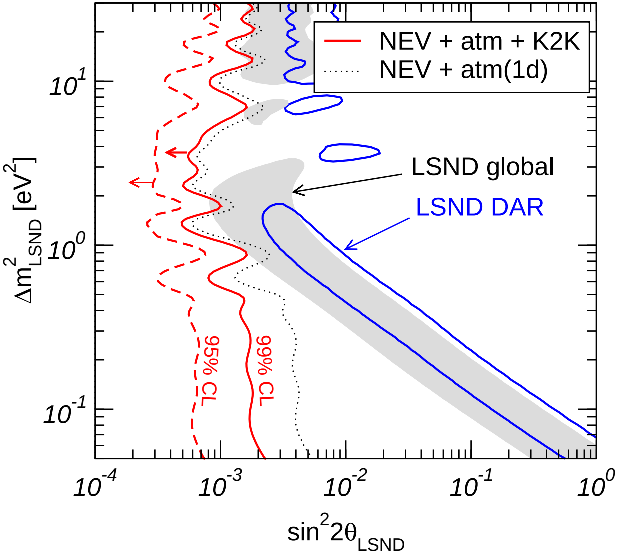
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

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

[Okada, Yasuda, Int. J. Mod. Phys. A12 (1997) 3669-3694, arXiv:hep-ph/9606411]

[Bilenky, Giunti, Grimus, Eur. Phys. J. C1 (1998) 247, arXiv:hep-ph/9607372]

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

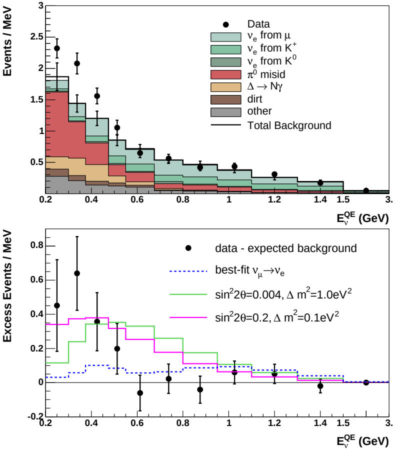


[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

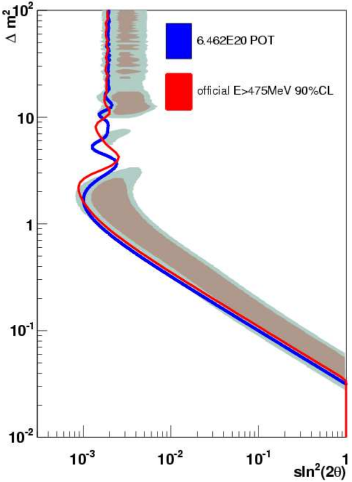
MiniBooNE Neutrinos

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

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



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



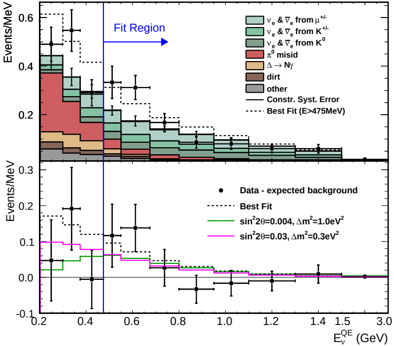
[Djurcic, arXiv:0901.1648]

Low-Energy Anomaly!

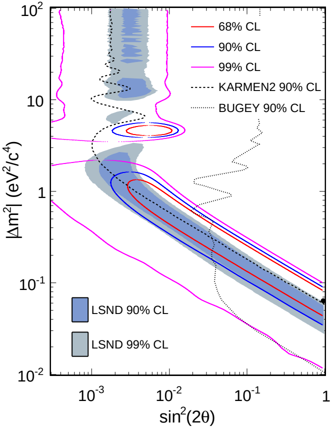
MiniBooNE Antineutrinos

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

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

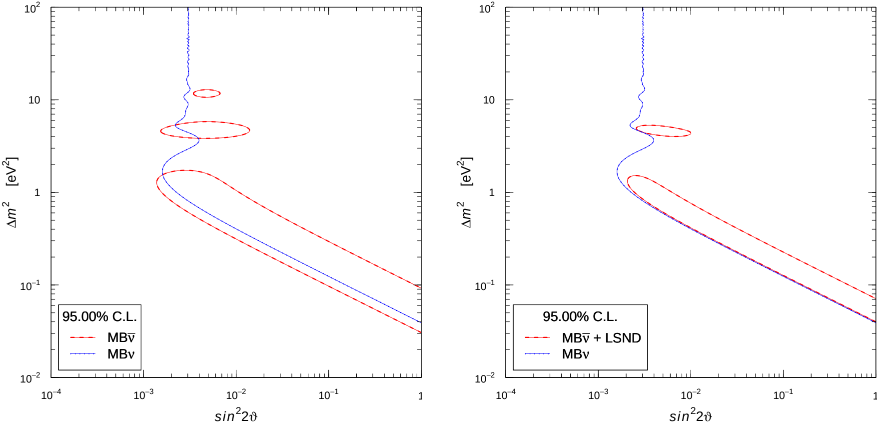


[MiniBooNE, PRL 105 (2010) 181801, arXiv:1007.1150]



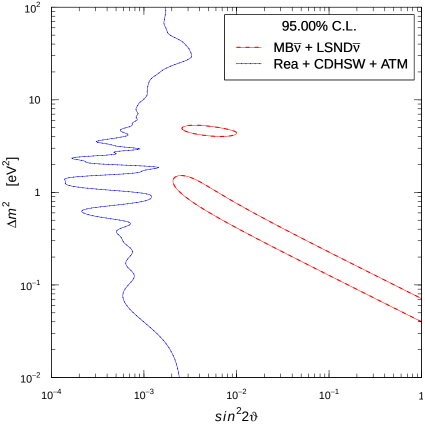
Agreement with LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal!

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

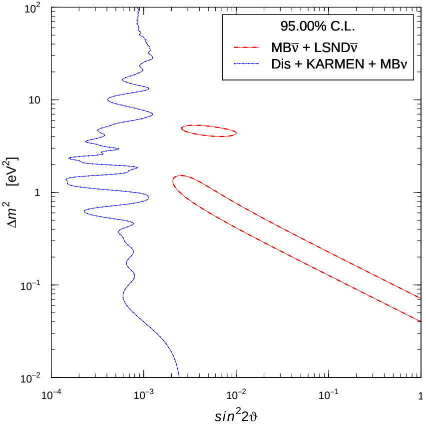


PGoF = 2.4% PGoF = 0.24%

- 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]



PGoF = 0.074%



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?

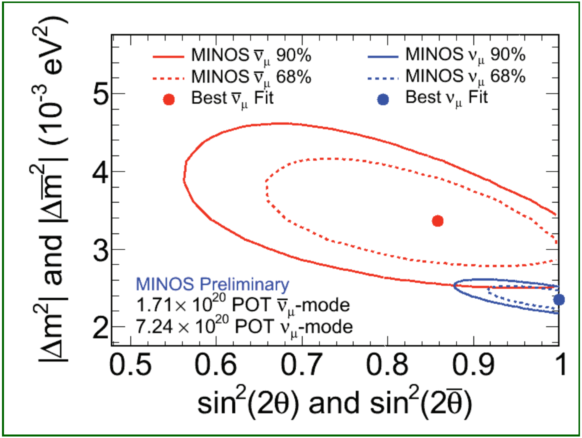
[Barger, Marfatia, Whisnant, PLB 576 (2003) 303]

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

MINOS Hint of CPT Violation

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

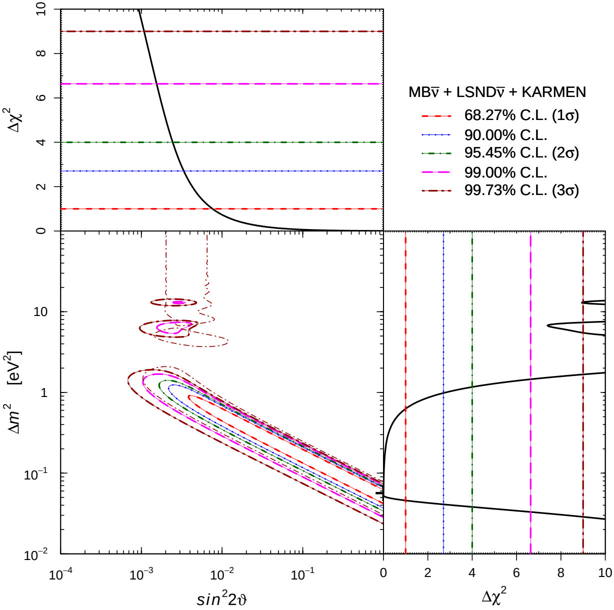
Near Detector at 1.04 km Far Detector at 734 km



[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

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

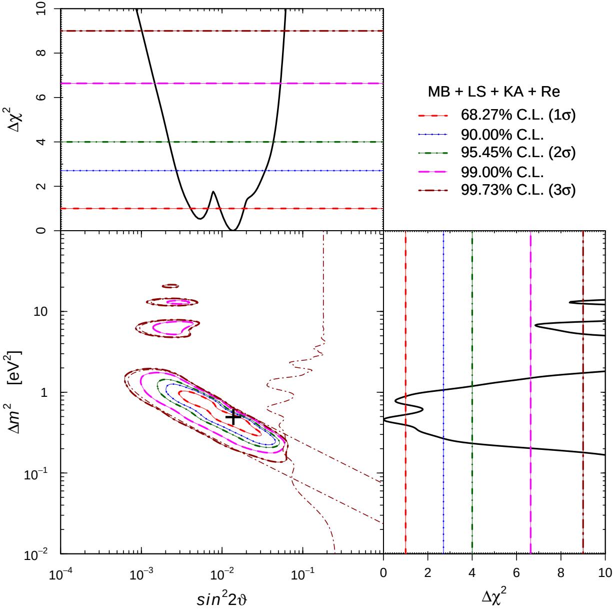
$$P_{\bar{\nu}_e \to \bar{\nu}_e} + P_{\bar{\nu}_\mu \to \bar{\nu}_e} + P_{\bar{\nu}_\tau \to \bar{\nu}_e} + P_{\bar{\nu}_s \to \bar{\nu}_e} = 1$$

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

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

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

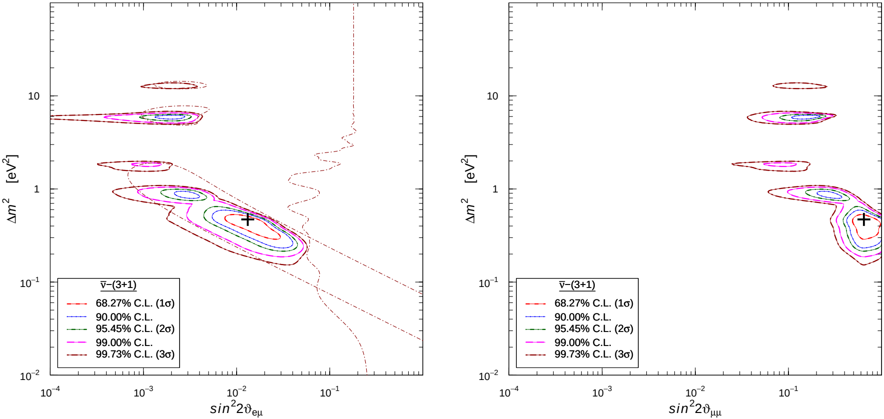
$\Delta\chi^2_{\text{min}} = 3.0$

$\text{NdF} = 2$

$\text{GoF} = 22\%$

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

Antineutrino Oscillations in 3+1 Schemes



$$\chi^2_{\text{min}} = 82.0 \qquad \text{NdF} = 83 \qquad \text{GoF} = 51\%$$

$$\Delta m^2 = 0.45\,\text{eV}^2 \quad \sin^2 2\vartheta_{e\mu} = 0.013 \quad \sin^2 2\vartheta_{ee} = 0.017 \quad \sin^2 2\vartheta_{\mu\mu} = 0.65$$

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

[Giunti, Laveder, arXiv:1012.0267]

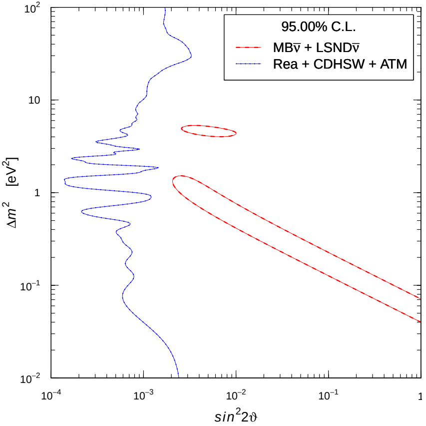
New Calculation of Reactor $\bar{\nu}_e$ Flux

- 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"

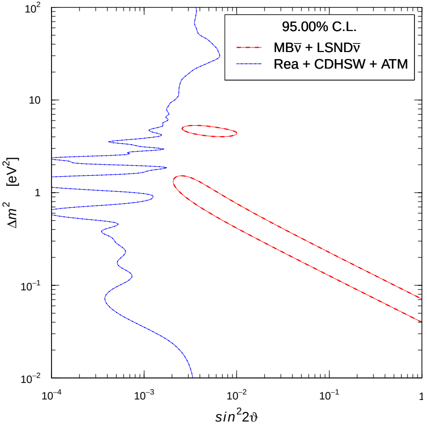
- New reactor neutrino flux has several implications: fit of solar and KamLAND data, determination of ϑ_{13}, short-baseline $\bar{\nu}_e$ disappearance, ...

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



PGoF $= 0.074\%$

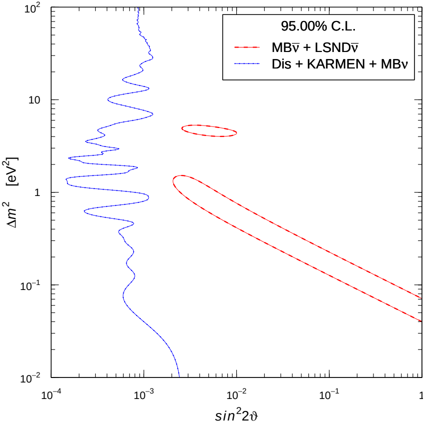
New Reactor $\bar{\nu}_e$ Fluxes



PGoF $= 0.27\%$

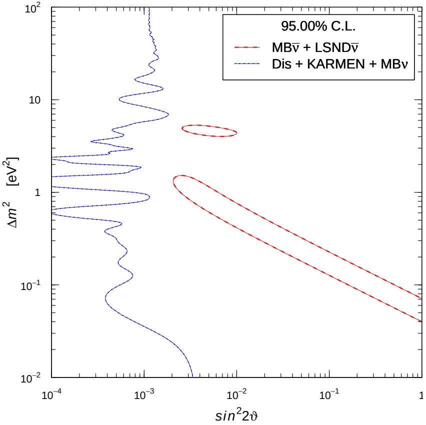
- New reactor neutrino flux evaluation decreases the tension between LSND + MiniBooNE and disappearance limits

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

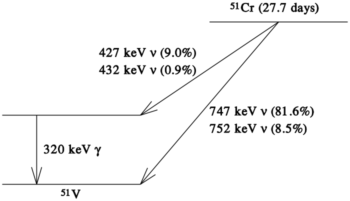
Gallium Radioactive Source Experiments

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

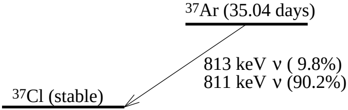
Detection Process: $\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$

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

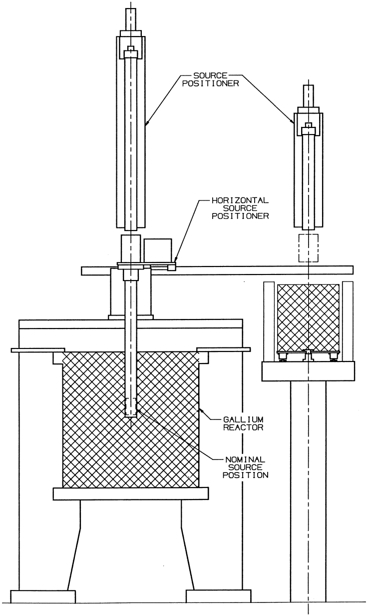
	^{51}Cr				^{37}Ar	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098



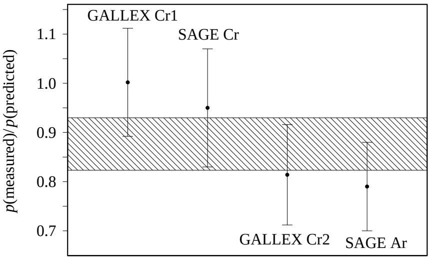
[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]



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



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



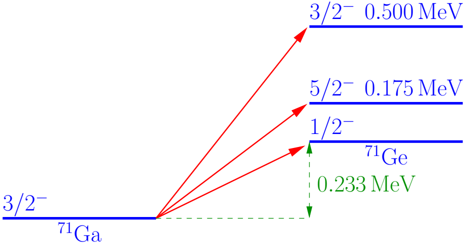
[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

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

- Deficit could be due to overestimate of

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

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



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

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

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

- 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: $\frac{\text{BGT}_{175\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = \frac{\text{BGT}_{500\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = 0$

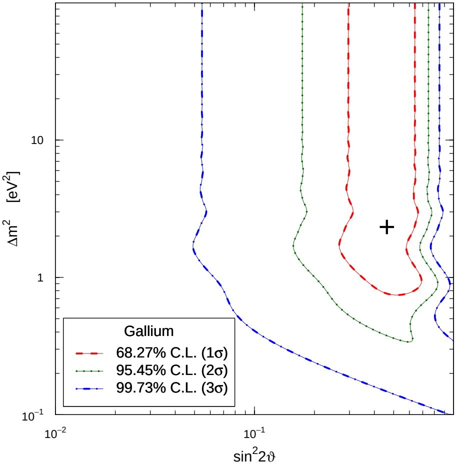
3σ upper limit: $\frac{\text{BGT}_{175\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \times 2 \qquad \frac{\text{BGT}_{500\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146 \times 2$

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

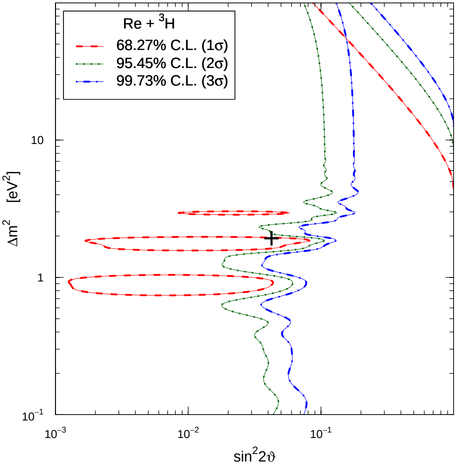
- Haxton: [Hata, Haxton, PLB 353 (1995) 422, nucl-th/9503017; Haxton, PLB 431 (1998) 110, nucl-th/9804011]

  “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.”

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



[Giunti, Laveder, arXiv:1006.3244]

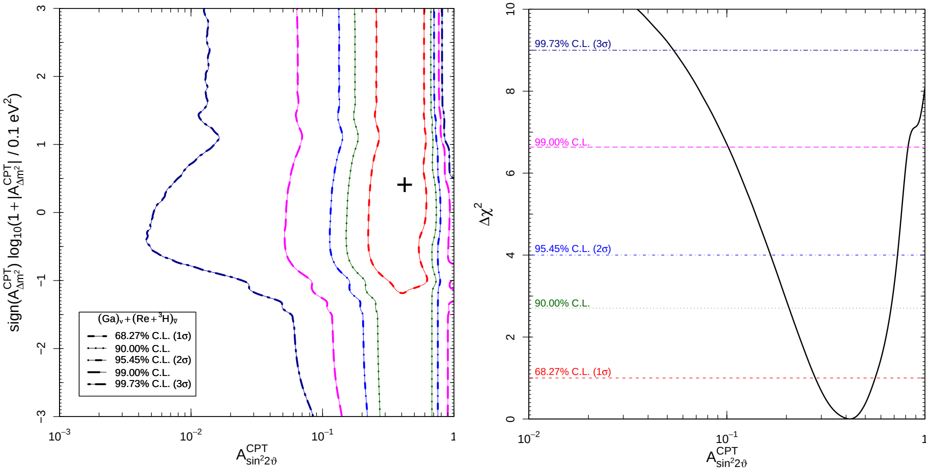


[Giunti, Laveder, PRD 82 (2010) 053005, arXiv:1005.4599]

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

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

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

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

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]

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

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

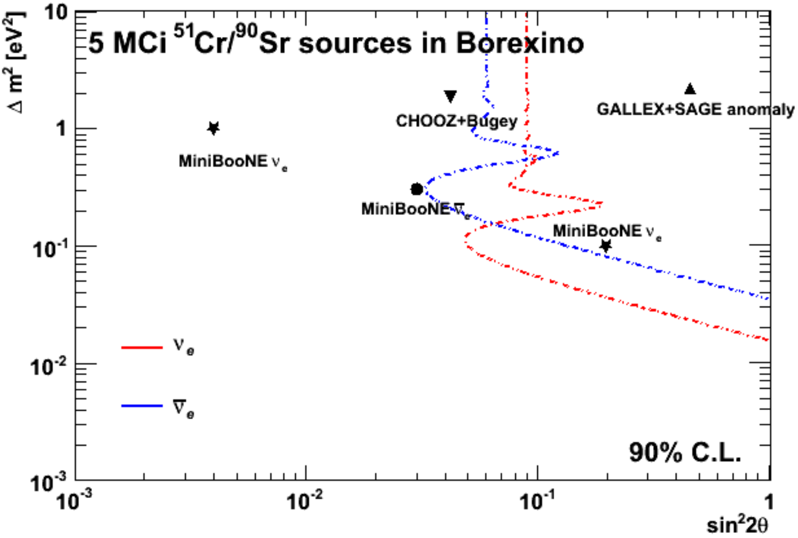
- New ν_e and $\bar{\nu}_e$ radioactive source experiments with low-threshold neutrino elastic scattering detectors.

- LENS (Low Energy Neutrino Spectroscopy): [Agarwalla, Raghavan, arXiv:1011.4509]

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

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

- 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!