Sterile Neutrino Fits

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NeuTel2011

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Collaboration with Marco Laveder (Padova University)

Three-Neutrino Mixing Paradigm

Solar $\nu_e \to \nu_\mu, \nu_\tau$	Homestake Kamiokande GALLEX/GNO & SAGE Super-Kamiokande SNO BOREXino	
Reactor $\bar{\nu}_e$ disappearance	(KamLAND)	

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

Atmospheric $\nu_\mu \to \nu_\tau$	Kamiokande IMB Super-Kamiokande MACRO Soudan-2	
Accelerator ν_μ disappearance	(K2K & MINOS)	

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

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

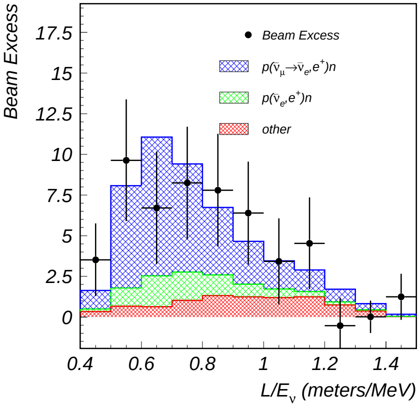
$$\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$$

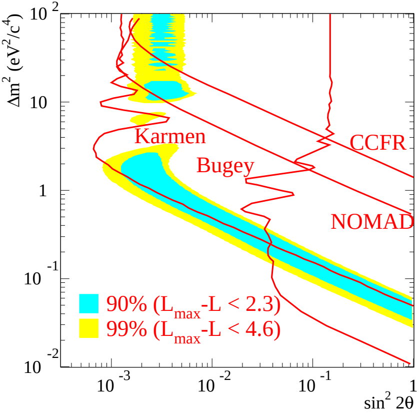
$$\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq 2.4 \times 10^{-3}\,\text{eV}^2$$

LSND

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

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



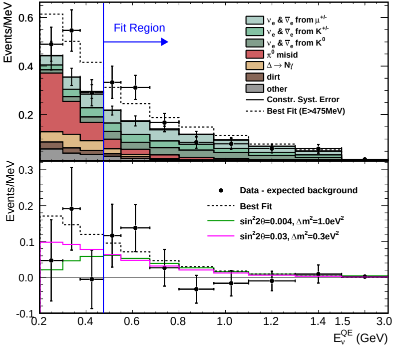


$\Delta m^2_{\text{LSND}} \gtrsim 0.2\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}})$

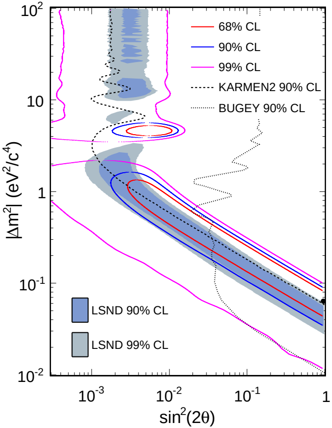
MiniBooNE Antineutrinos

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

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



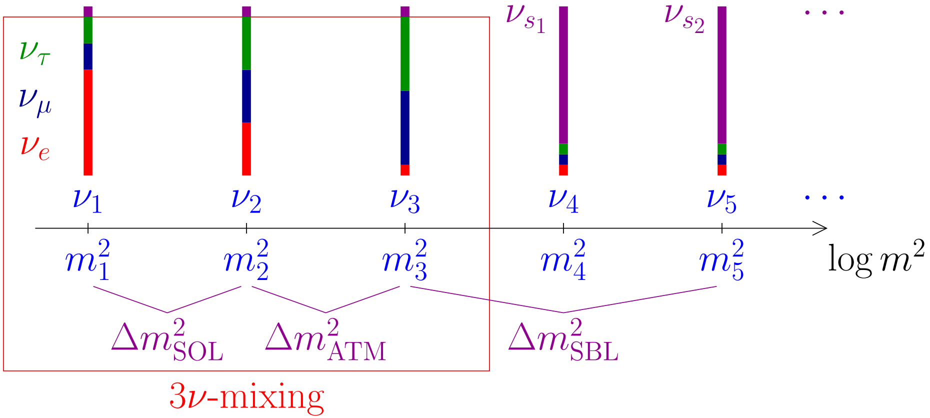
[MiniBooNE, PRL 105 (2010) 181801, arXiv:1007.1150]



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

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

Beyond Three-Neutrino Mixing



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
- Dirac mass $m_\mathrm{D}\overline{\nu_R}\nu_L$ + Majorana mass $m_\mathrm{M}\overline{\nu_R^c}\nu_R$
- $\nu_{eL}\,,\ \nu_{\mu L}\,,\ \nu_{\tau L}\ +\ \nu_{eR}\,,\ \nu_{\mu R}\,,\ \nu_{\tau R} \quad \Longrightarrow$ 6 massive Majorana neutrinos

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
- Powerful window on new physics beyond the Standard Model

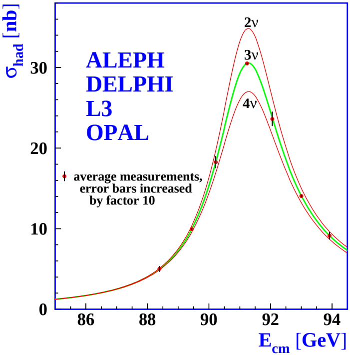
How many Sterile Neutrinos?

$$e^+e^- \to Z \xrightarrow{\text{invisible}} \sum_{a=\text{active}} \nu_a \bar{\nu}_a$$

[LEP, Phys. Rept. 427 (2006) 257, hep-ex/0509008]

3 light active flavor neutrinos

$$\nu_e \quad \nu_\mu \quad \nu_\tau$$



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

$N \geq 3$
no upper limit!

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

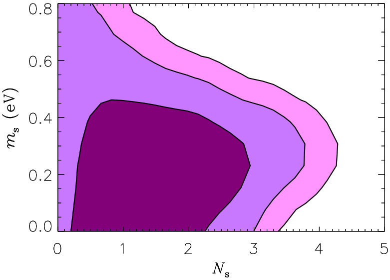
Flavor Basis: $\nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_{s_1} \quad \nu_{s_2} \quad \cdots$

ACTIVE STERILE

Cosmology

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

- CMB and LSS in ΛCDM:



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

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

[Giusarma, Corsi, Archidiacono, de Putter, Melchiorri, Mena, Pandolfi, arXiv:1102.4774]

- BBN:

$N_s = 0.22 \pm 0.59$ [Cyburt, Fields, Olive, Skillman, AP 23 (2005) 313, astro-ph/0408033]

$N_s = 0.64^{+0.40}_{-0.35}$ [Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440]

SBL Oscillation Probabilities in 3+1 Schemes

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

No CP Violation!

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

Perturbation of 3ν Mixing

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

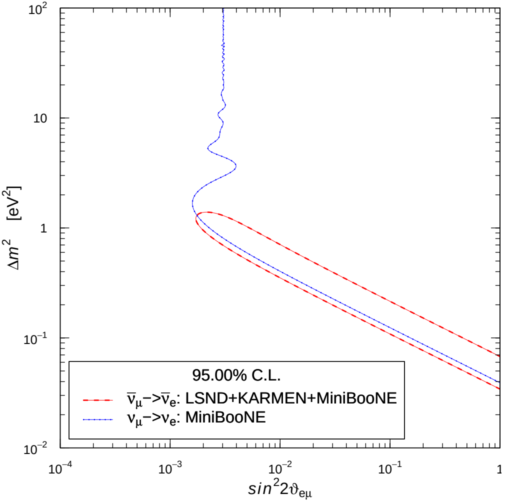
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \boxed{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL (fourth column)

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

$$\Downarrow$$

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



3+1 Schemes

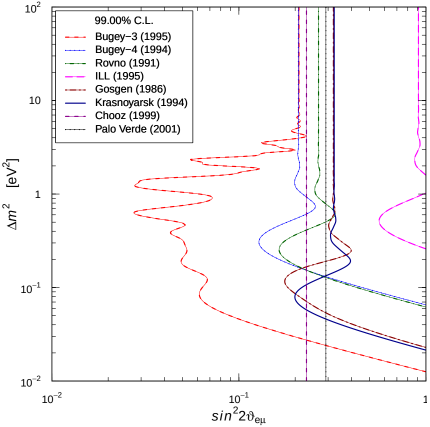
GoF = 32%

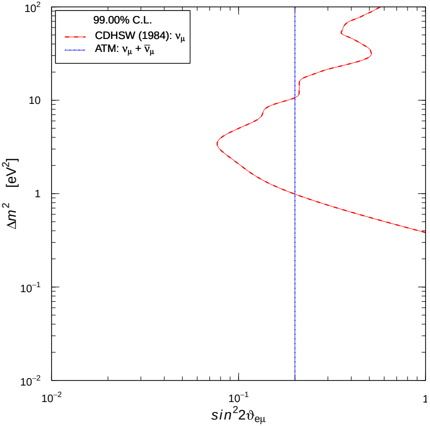
PGoF = 0.89%

- Tension between LSND + KARMEN + 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]

$\bar{\nu}_e$ Disappearance

ν_μ and $\bar{\nu}_\mu$ Disappearance





- ν_e disappearance experiments:

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

- ν_μ disappearance experiments:

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

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

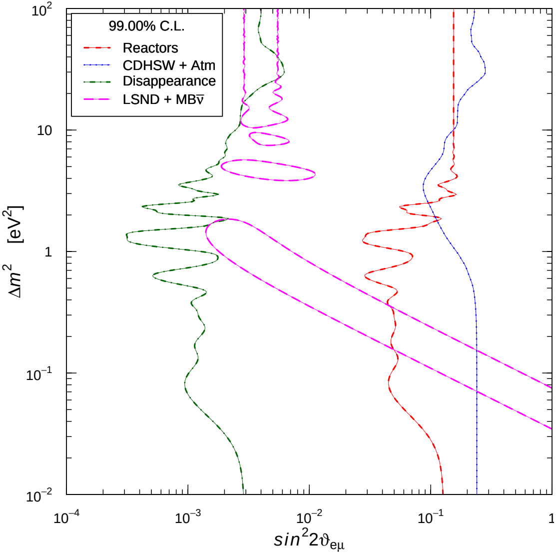
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

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

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

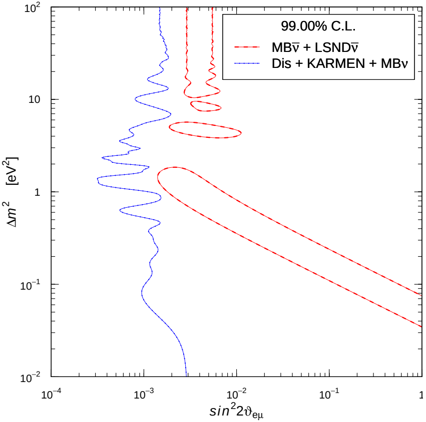
[Bilenky, Giunti, Grimus, Eur. Phys. J. C1 (1998) 247, arXiv:hep-ph/9607372]

3+1 Schemes



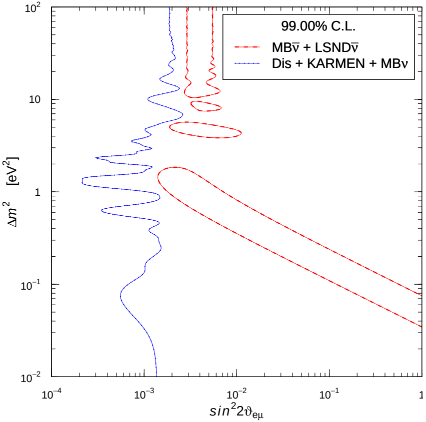
99.00% C.L.
Reactors
CDHSW + Atm
Disappearance
LSND + MB$\bar{\nu}$
Δm^2 [eV^2]
10^2
10
1
10^{-1}
10^{-2}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$sin^2 2\vartheta_{e\mu}$

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



$\mathrm{PGoF} = 0.0052\%$

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



$\mathrm{PGoF} = 0.010\%$

- Strong tension between $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance and disappearance limits ($\bar{\nu}_e \to \bar{\nu}_e$ and mainly $\nu_\mu \to \nu_\mu$)
- Tension reduced in 3+2, 3+3, ...schemes and in 3+1+NSI
- CPT Violation?

[Barger, Marfatia, Whisnant, PLB 576 (2003) 303]
[Giunti, Laveder, PRD 82 (2010) 093016, arXiv:1010.1395; arXiv:1012.0267]

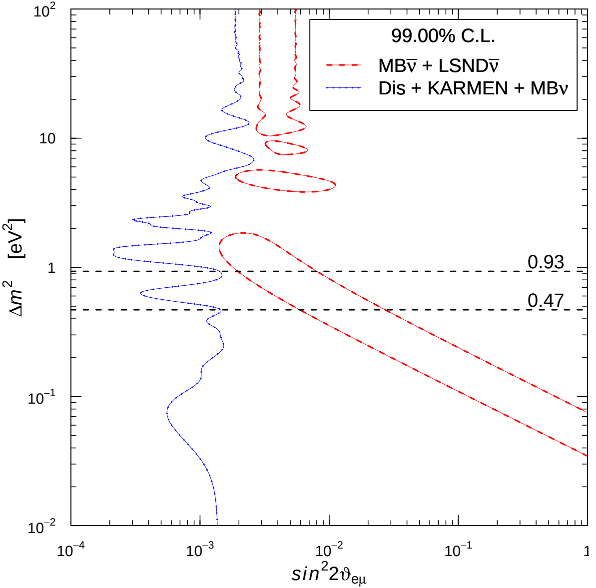
3+2 Fit: Talk by T. Schwetz

$\Delta m^2_{51,\mathrm{bf}} = 0.93\,\mathrm{eV}^2$

$\Delta m^2_{41,\mathrm{bf}} = 0.47\,\mathrm{eV}^2$

PGoF $\sim 1\%$

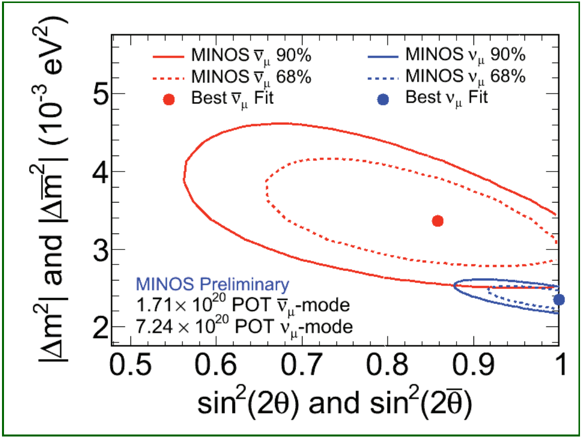
New Reactor $\bar{\nu}_e$ Fluxes!



MINOS Hint of CPT Violation?

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

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



[MINOS, Neutrino 2010, 14 June 2010]

CDF Hint of CPT Violation?

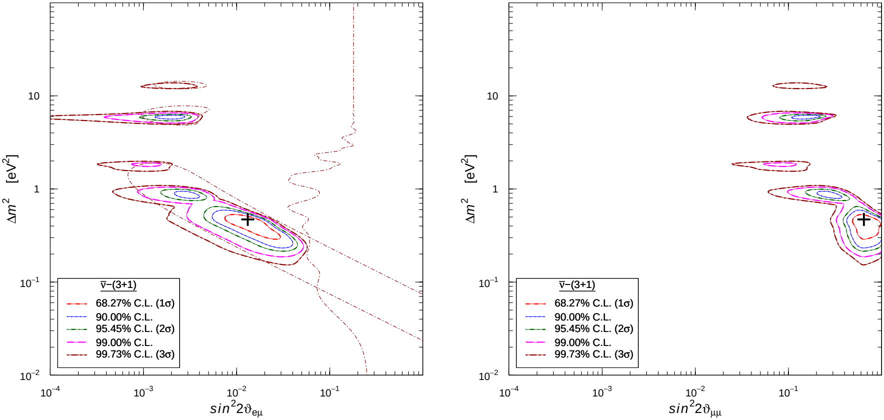
Measurement of the mass difference between t and $\bar{t}$ quarks,

arXiv:1103.2782v1 [hep-ex] 16 March 2011

$$m_t - m_{\bar{t}} = -3.3 \pm 1.4 \pm 1.0\,\mathrm{GeV}$$

"approximately two standard deviations away from the CPT hypothesis of zero mass difference"

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]

Gallium Anomaly

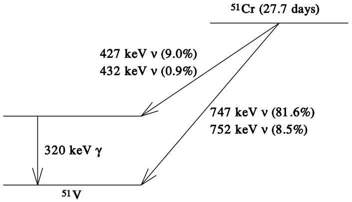
Gallium Radioactive Source Experiments

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

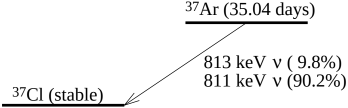
Detection Process: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

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

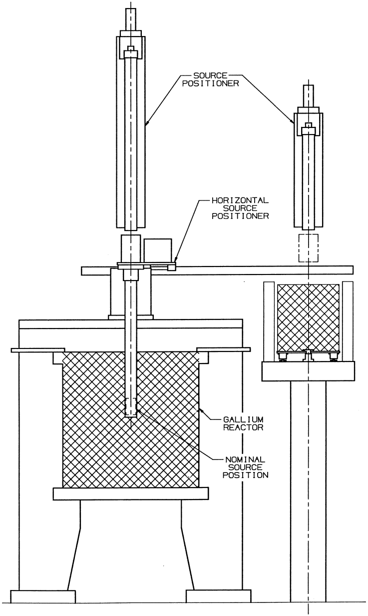
	^{51}Cr				^{37}Ar	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098



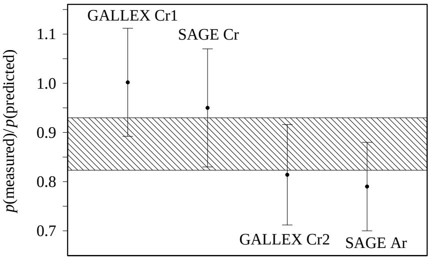
[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]



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

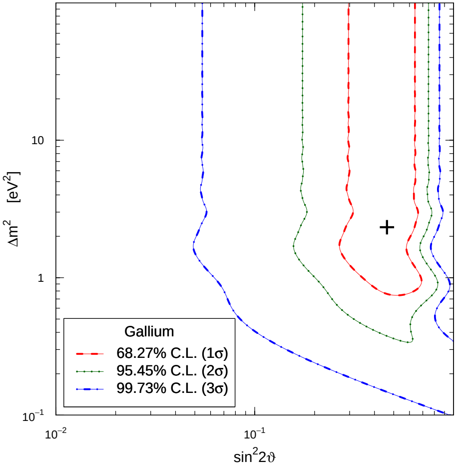


[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]

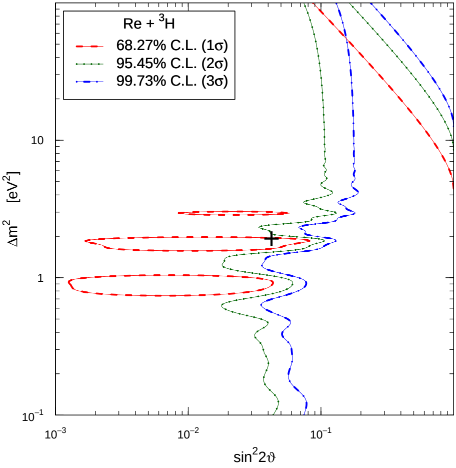


[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

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



[Giunti, Laveder, arXiv:1006.3244]



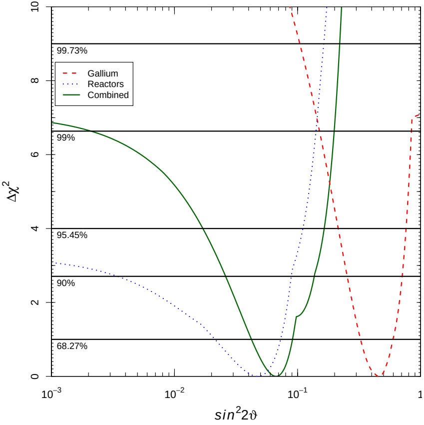
[Giunti, Laveder, PRD 82 (2010) 053005, arXiv:1005.4599]

$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2$ is OK, but $\sin^2 2\vartheta_{\nu} > \sin^2 2\vartheta_{\bar{\nu}}$

Parameter Goodness of Fit = 0.2%

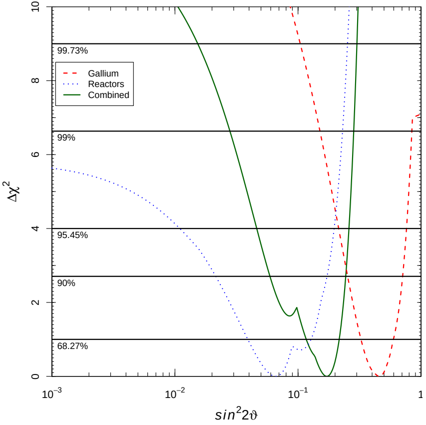
CPT violation? [Giunti, Laveder, PRD 82 (2010) 113009, arXiv:1008.4750]

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



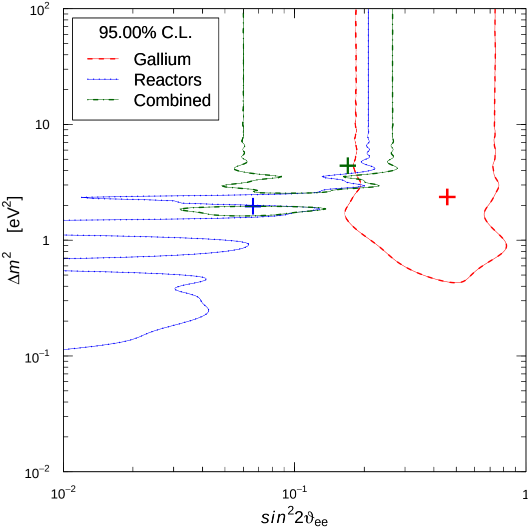
PGoF = 0.27%

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



PGoF = 1.1%

Gallium Anomaly + Reactor Anomaly



$\chi^2_{\text{min}} = 59.8$

$\text{NdF} = 65$

$\text{GoF} = 66\%$

$\sin^2 2\vartheta = 0.17$

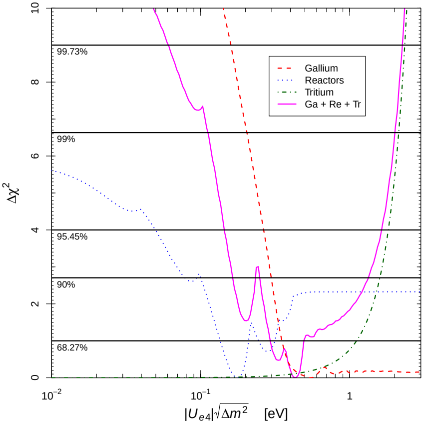
$\Delta m^2 = 4.17\,\text{eV}^2$

$\text{PGoF} = 1.1\%$

see also the talk by T. Lasserre

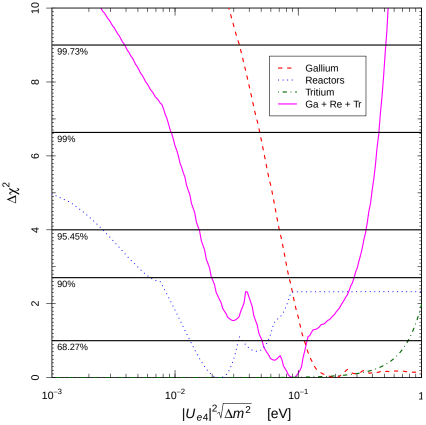
Implications of Gallium and Reactor Anomalies

β Decay



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

$(\beta\beta)_{0\nu}$ Decay



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

[Giunti, Laveder, In Preparation]

Conclusions 1

- Suggestive LSND and MiniBooNE agreement on SBL $\bar{\nu}_\mu \to \bar{\nu}_e$
- Hint in favor of sterile neutrinos is compatible with cosmological data, but mass is limited
- Two experimental tensions:
  - LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ vs MiniBooNE $\nu_\mu \to \nu_e$ (CP violation?)
  - LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ vs $\bar{\nu}_e$ and ν_μ disappearance limits
- CPT-invariant 3+1 Four-Neutrino Mixing is strongly disfavored (no CP violation and tension between appearance and disappearance)
- 3+2 can explain CP violation and reduce tension between appearance and disappearance with New Reactor $\bar{\nu}_e$ Fluxes [talk by T. Schwetz]
- 3+1+NSI has CP violation and reduced appearance-disappearance tension
- CPT-violating 3+1 Mixing $\Longrightarrow$ large SBL $\bar{\nu}_\mu$ disappearance

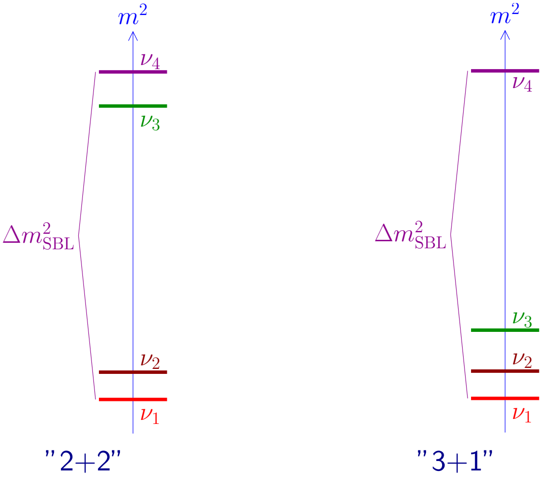
Conclusions 2

- Interesting agreement of
  - Gallium Anomaly (SBL ν_e disappearance)
  - Reactor Anomaly (SBL $\bar{\nu}_e$ disappearance)
- Testable Predictions:
  - $m_\beta \sim 0.14 - 1.63\,\text{eV} \quad (2\sigma)$
  - $m_{\beta\beta} \sim 0.02 - 0.35\,\text{eV} \quad (2\sigma)$

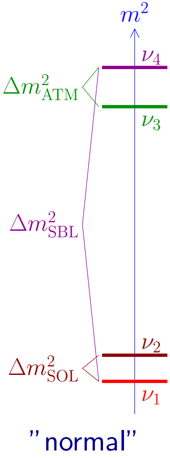
- Work in Progress: combined explanation of LSND and MiniBooNE + Gallium and Reactor Anomalies
- New short-baseline neutrino oscillation experiments are needed!
  - ICARUS@CERN-PS [next talk by C. Rubbia]
  - new SAGE radioactive source experiment [poster by V. Gorbachev]
  - Borexino radioactive source experiment [Ianni, Montanino, Scioscia, EPJC 8 (1999) 609, arXiv:hep-ex/9901012]
  - ...

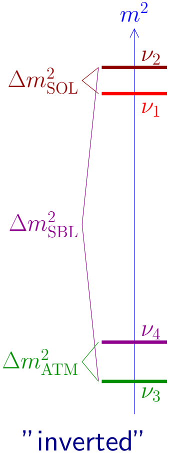
Backup Slides

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

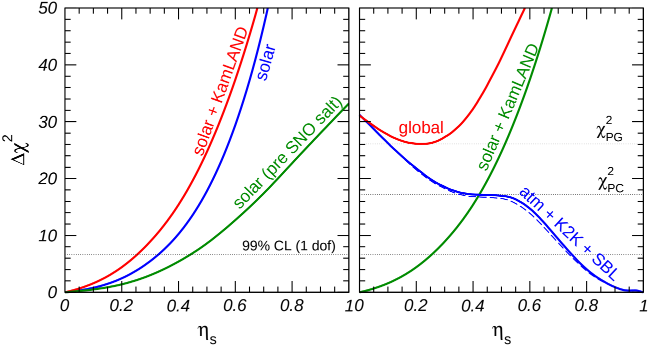


2+2 Four-Neutrino Schemes





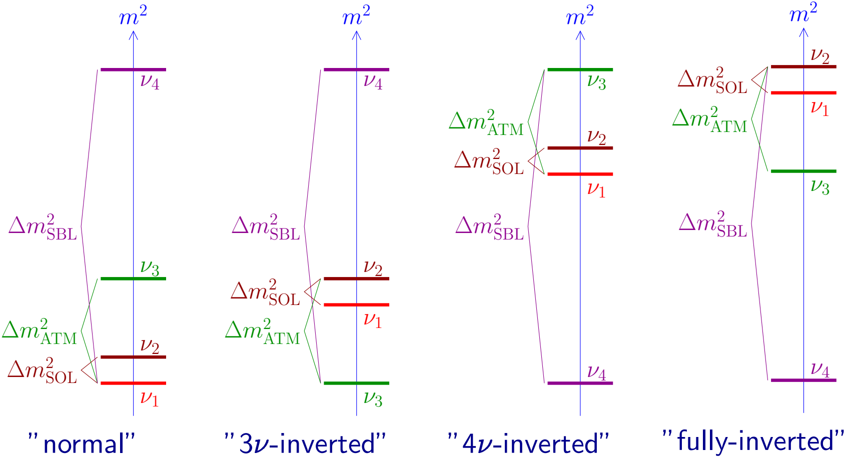
2+2 Schemes are strongly disfavored by solar and atmospheric data



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

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

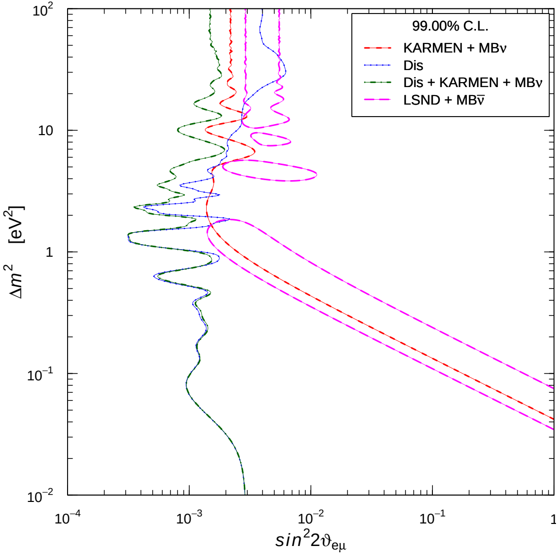
3+1 Four-Neutrino Schemes



Perturbation of 3-ν Mixing

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

3+1 Schemes



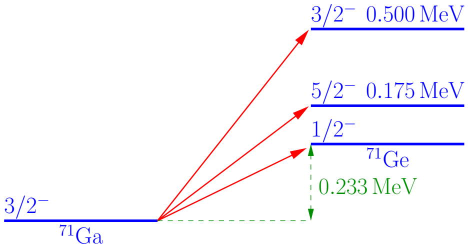
99.00% C.L.
KARMEN + MBν
Dis
Dis + KARMEN + MBν
LSND + MBν̄
10^2
10
1
10^{-1}
10^{-2}
Δm^2 [eV^2]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$sin^2 2\vartheta_{e\mu}$

Gallium Anomaly

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

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

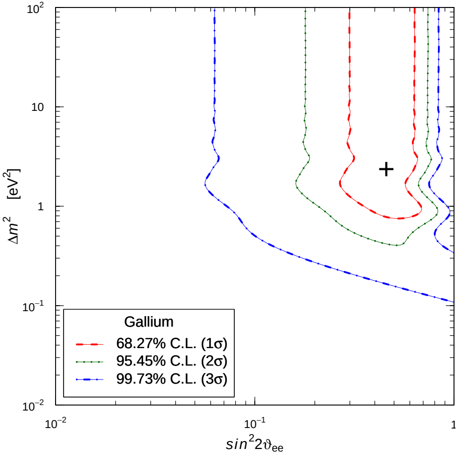
  $$\sigma({}^{51}\text{Cr}) = 58.1 \times 10^{-46}\,\text{cm}^2 \left(1^{+0.036}_{-0.028}\right)_{1\sigma} \implies \boxed{R_{\text{Ga}} = 0.86 \pm 0.05}$$

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

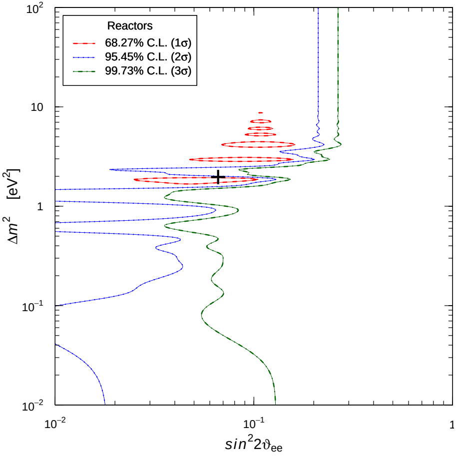
  "a sophisticated shell model calculation is performed ... for the transition to the first excited state in ^{71}Ge. The calculation predicts destructive interference between the (p, n) spin and spin-tensor matrix elements."

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

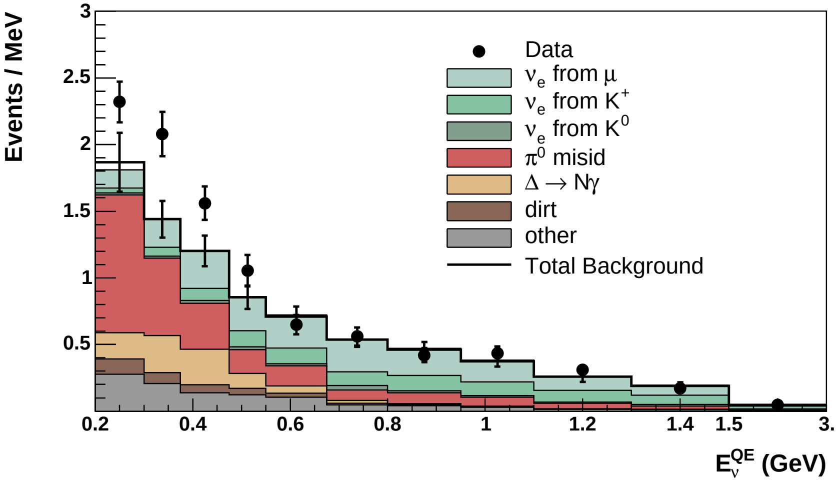
Gallium Anomaly



Reactor Anomaly



MiniBooNE Low-Energy Anomaly



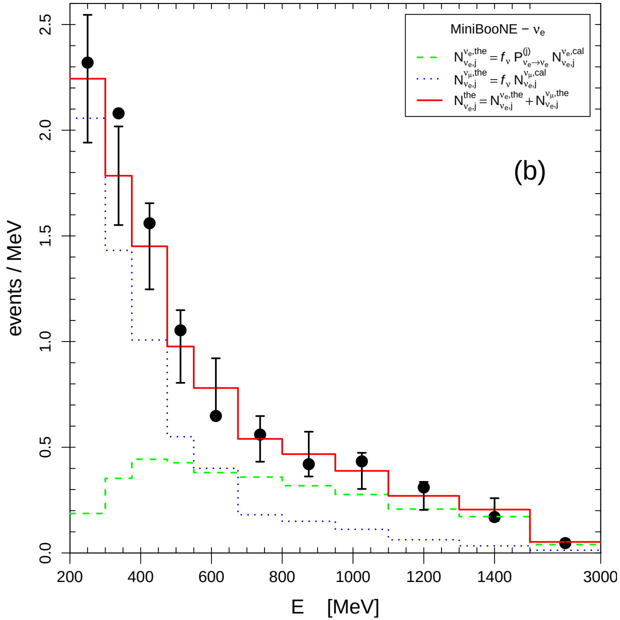
[PRL 102 (2009) 101802, arXiv:0812.2243]

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]

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

- 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/



No Osc. & $f_\nu = 1$

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

$\mathrm{NdF} = 3 + 16$

$\mathrm{GoF} = 41\%$

Our Hypothesis

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

$\mathrm{NdF} = 16$

$\mathrm{GoF} = 89\%$

$f_\nu = 1.26$

$\sin^2 2\vartheta = 0.32$

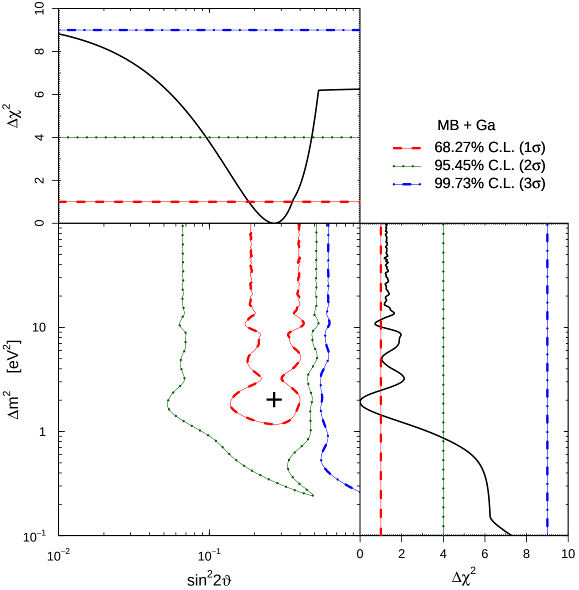
$\Delta m^2 = 1.84\,\mathrm{eV}^2$

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

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

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

MiniBooNE + Gallium



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

$\mathrm{NdF} = 20$

$\mathrm{GoF} = 93\%$

$\sin^2 2\vartheta = 0.27$

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

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

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]

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

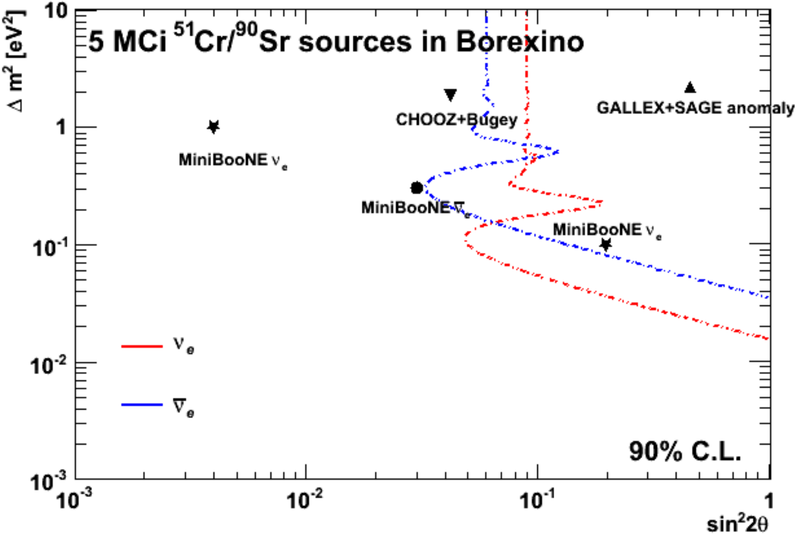
$$\mu^- \to \nu_\mu + e^- + \bar{\nu}_e$$

- 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]