# Physics of Sterile Neutrinos

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# Standard Model: Massless Neutrinos

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

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

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

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

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

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

(no Higgs triplet)

# Extension of the SM: Massive Neutrinos

Standard Model can be extended with $\nu_R$ ($e_L, e_R$; $u_L, u_R$; $d_L, d_R$; ...)

$\nu_L + \nu_R \Rightarrow$ Dirac neutrino mass term $\mathcal{L}^{\mathrm{D}} \sim m^{\mathrm{D}} \overline{\nu_L} \nu_R \Rightarrow m^{\mathrm{D}} \lesssim 100\,\mathrm{GeV}$

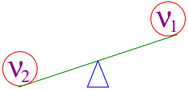
surprise: Majorana neutrino mass for $\nu_R$ is allowed! $\mathcal{L}^{\mathrm{M}}_R \sim m^{\mathrm{M}}_R \overline{(\nu^c)_L} \nu_R$

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

$m^{\mathrm{M}}_R$ 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-$\nu$ mixing

[Minkowski, PLB 67 (1977) 42]

[Yanagida (1979); Gell-Mann, Ramond, Slansky (1979); Mohapatra, Senjanovic, PRL 44 (1980) 912]

- Neutrinos are special in the Standard Model: the only neutral fermions
- In extensions of SM neutrinos can mix with non-SM fermions
- SM: $L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$ $\widetilde{\Phi} = i\sigma_2 \, \Phi^* = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \xrightarrow[\text{Breaking}]{\text{Symmetry}} \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$
- $\overline{L_L}\widetilde{\Phi}$ can couple to new non-SM chiral fermion field $f_R$
- Dirac mass term $\sim \overline{L_L}\widetilde{\Phi} f_R \quad + \quad$ Majorana mass term $\sim \overline{f_R^C} f_R$
- $f_R$ is often called Right-Handed Neutrino: $f_R \to \nu_R$
- A light $\nu_R$ is called Sterile Neutrino

# 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 $(\nu_s)$

- Observables:
  - disappearance of Active Neutrinos
  - 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!

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| Mass Basis: | $\nu_1$ | $\nu_2$ | $\nu_3$ | $\nu_4$ | $\nu_5$ | $\cdots$ |
| Flavor Basis: | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ | $\nu_{s_1}$ | $\nu_{s_2}$ | $\cdots$ |
|  | 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
$\nu_\mu$ 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 $\Delta m^2$ $\Longleftrightarrow$ Three-Neutrino Mixing

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

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

- 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-$\nu$ Mixing

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

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

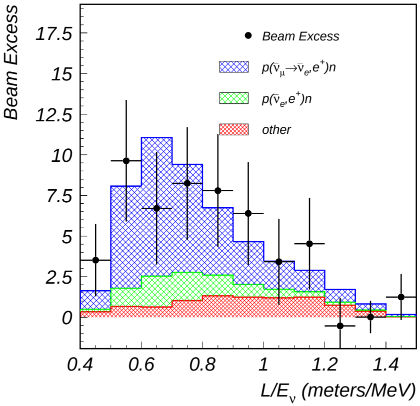
Flavor Basis: $\nu_e \quad \nu_\mu \quad \nu_\tau \quad \nu_s$

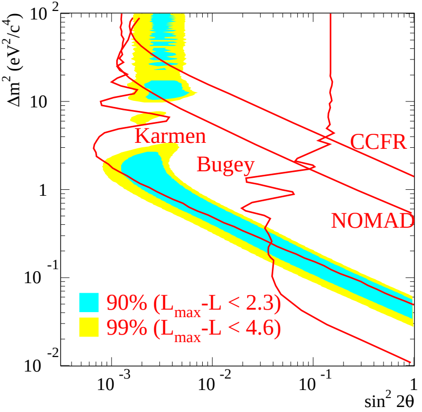
- Effective SBL Oscillation Probabilities:
  - $P^{\text{SBL}}_{\nu_\alpha \to \nu_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{\text{SBL}} L}{4E}\right) \qquad (\alpha \neq \beta)$
  - $P^{\text{SBL}}_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{\text{SBL}} L}{4E}\right)$

# LSND

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

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

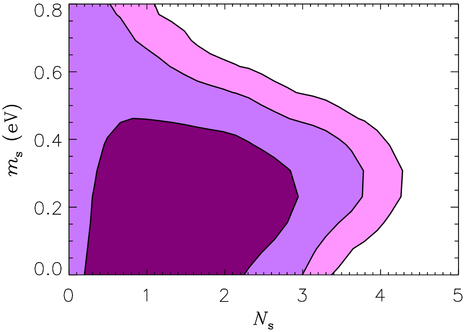




$$\Delta m^2_{\text{LSND}} \gtrsim 0.2\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}})$$

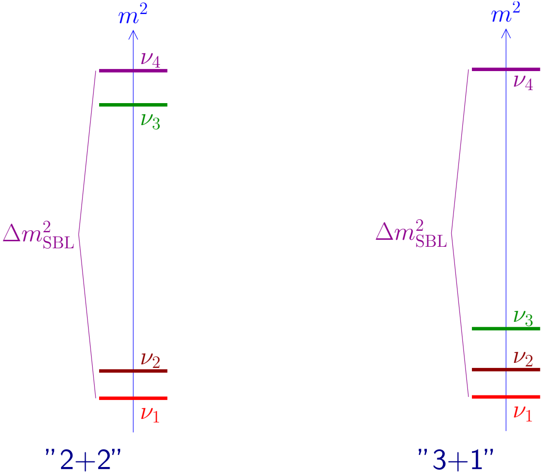
# Cosmology

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

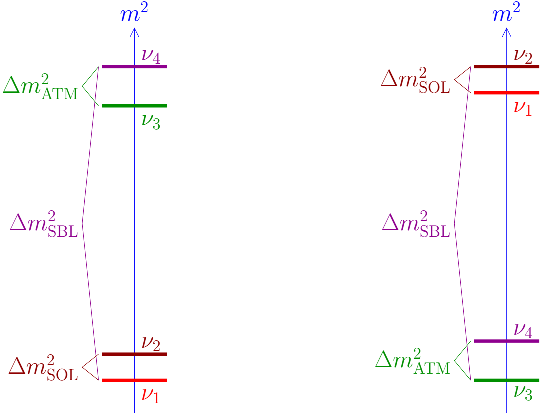


- BBN: $N_s = 0.68^{+0.80}_{-0.70}$ [Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440]

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

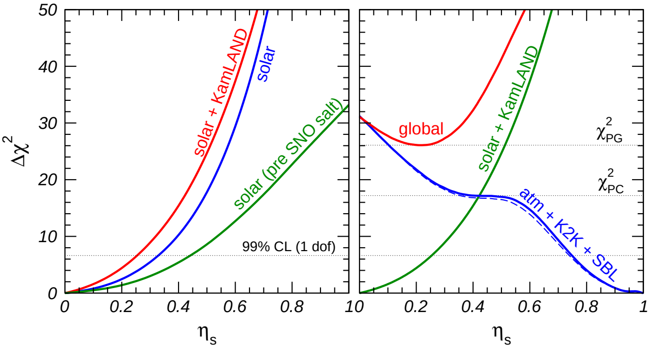


# 2+2 Four-Neutrino Schemes



"normal" "inverted"

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

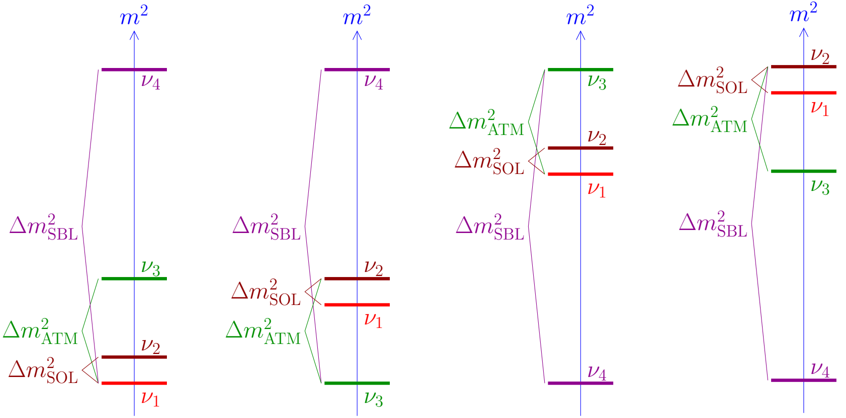


[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

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

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

# 3+1 Four-Neutrino Schemes



"normal" "3$\nu$-inverted" "4$\nu$-inverted" "fully-inverted"

Perturbation of 3-$\nu$ Mixing

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

# Effective SBL Oscillation Probability in 3+1 Schemes

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

No CP Violation!

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

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

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

↑ SBL

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

$$\Downarrow$$

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

- $\nu_e$ disappearance experiments:

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

- $\nu_\mu$ disappearance experiments:

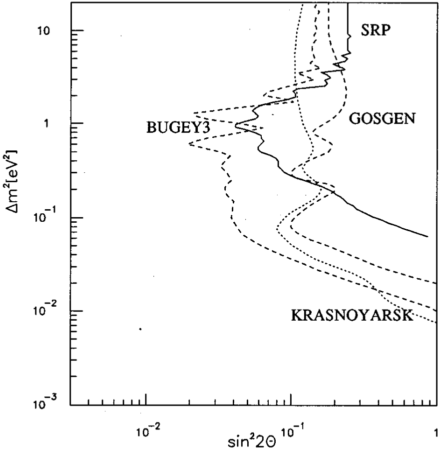
$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 \left(1 - |U_{\mu4}|^2\right) \simeq 4|U_{\mu4}|^2$$

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

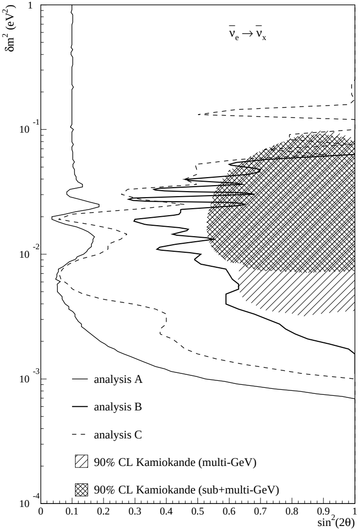
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$

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

# $\bar{\nu}_e$ Disappearance

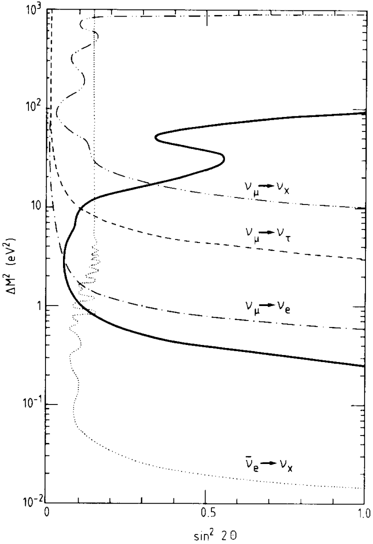


[Savannah River (SRP), PRD 53 (1996) 6054]

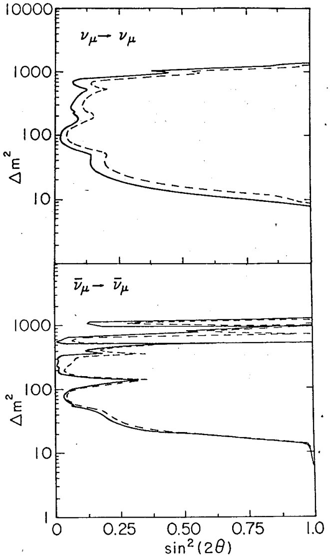


[CHOOZ, Eur. Phys. J. C27 (2003) 331, hep-ex/0301017]

# $\nu_\mu$ and $\bar{\nu}_\mu$ Disappearance

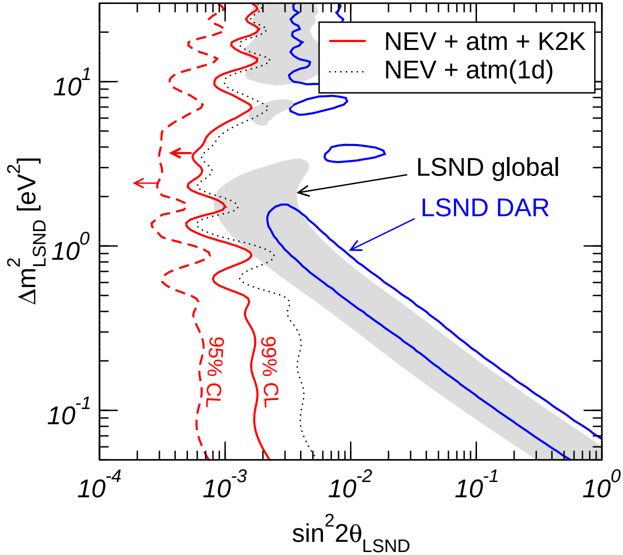


[CDHSW, PLB 134 (1984) 281]



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

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

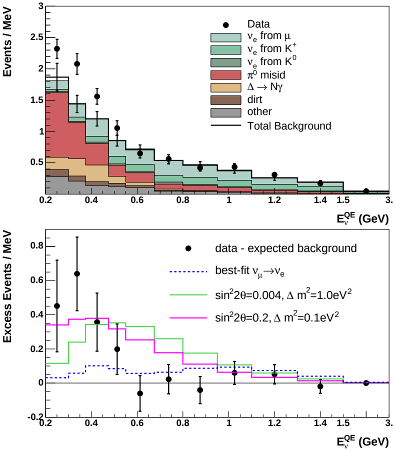


[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

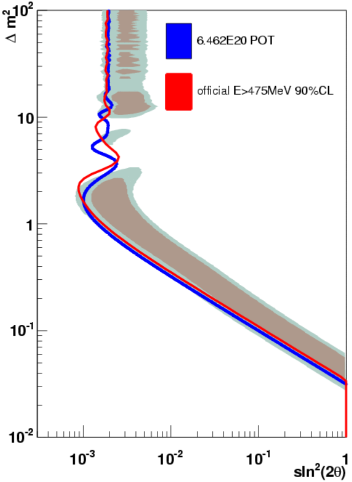
# MiniBooNE Neutrinos

[PRL 98 (2007) 231801]

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



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



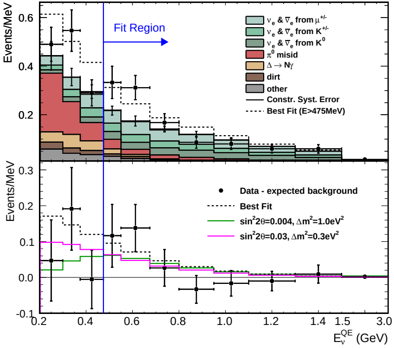
[arXiv:0901.1648]

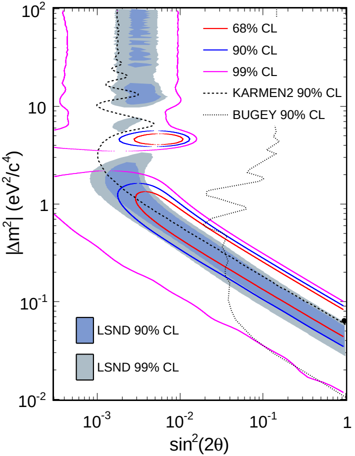
Low-Energy Anomaly!

# MiniBooNE Antineutrinos

[arXiv:1007.1150]

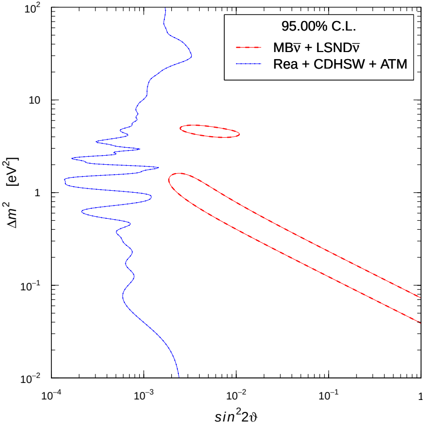
$\bar{\nu}_\mu \to \bar{\nu}_e$ $L \simeq 541\,\mathrm{m}$ $475\,\mathrm{MeV} \leq E \lesssim 3\,\mathrm{GeV}$



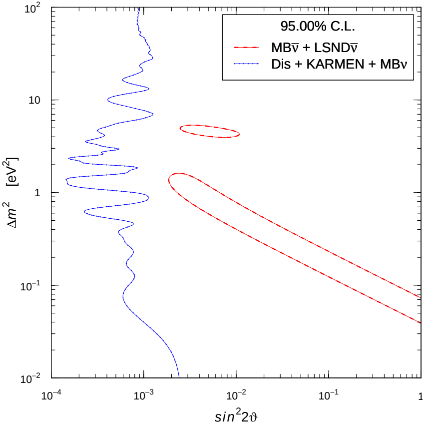


Agreement with LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal!

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



PGoF = 0.11%

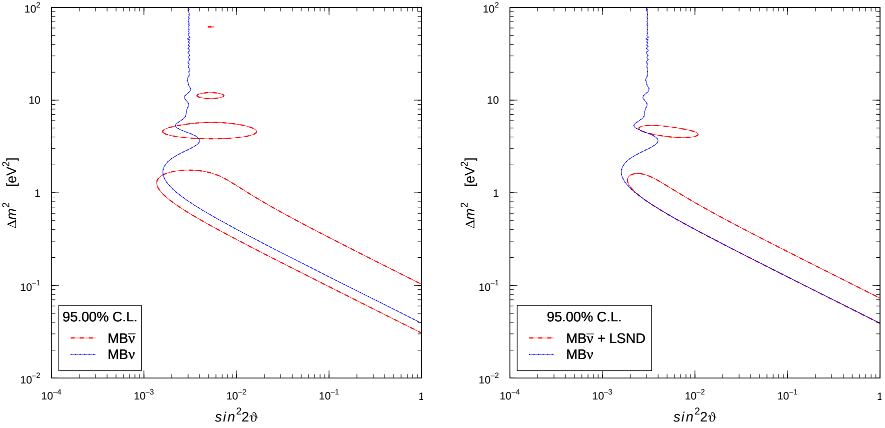


PGoF = 0.0095%

# 3+1 Schemes

Strong tension between LSND and 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 $\nu_\mu \to \nu_e$

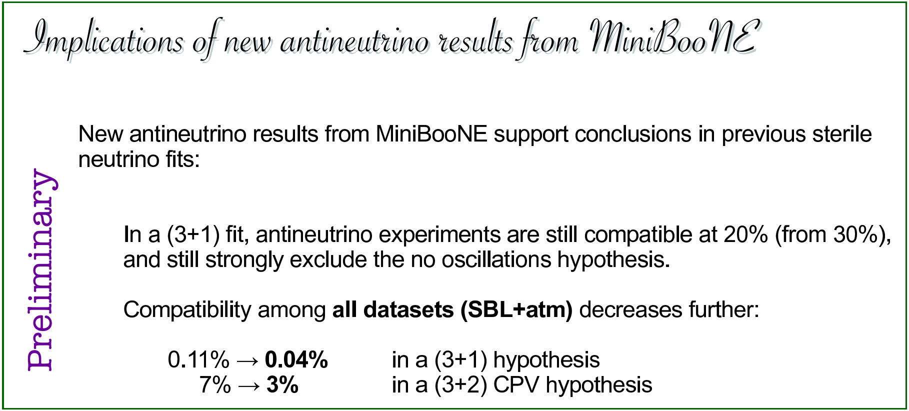


PGoF = 2.2% PGoF = 0.27%

3+1 Schemes: Strong tension between

- LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$
- MiniBooNE $\nu_\mu \to \nu_e$

# CP Violation: 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]

# Other Approaches

- Evgeny Akhmedov, Thomas Schwetz, arXiv:1007.4171, “MiniBooNE and LSND data: non-standard neutrino interactions in a (3+1) scheme versus (3+2) oscillations”: 1 or 2 sterile neutrinos and non-standard interactions

- Sergei Gninenko, arXiv:1009.5536, “A resolution of puzzles from the LSND, KARMEN, and MiniBooNE experiments”: radiative decay of a heavy sterile neutrino

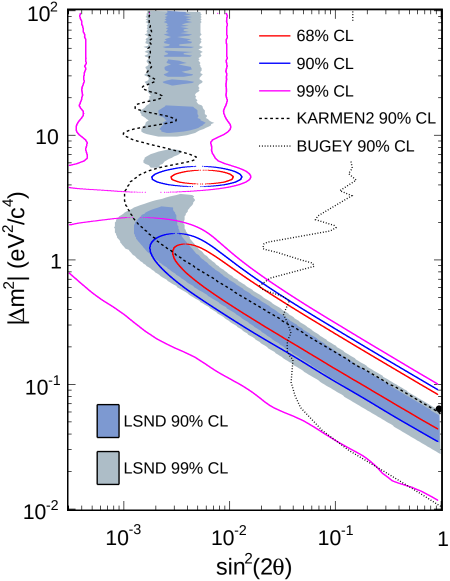
- Ann E Nelson, arXiv:1010.3970, “Effects of CP Violation from Neutral Heavy Fermions on Neutrino Oscillations, and the LSND/MiniBooNE Anomalies”: heavy sterile neutrinos and non-unitarity of mixing matrix

All these possibilities involve sterile neutrinos!

# CPT Violation?

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

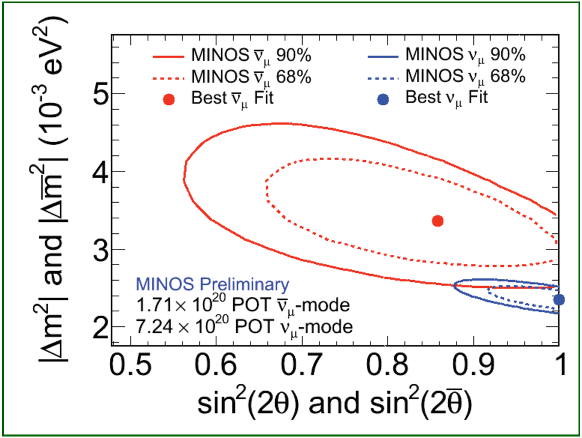
  [Barger, Marfatia, Whisnant, PLB 576 (2003) 303]
- LSND and MiniBooNE allowed regions are limited only by KARMEN and Bugey



# MINOS Hint of CPT Violation

LBL $\nu_\mu$ disappearance $E \sim 3\,\text{GeV}$

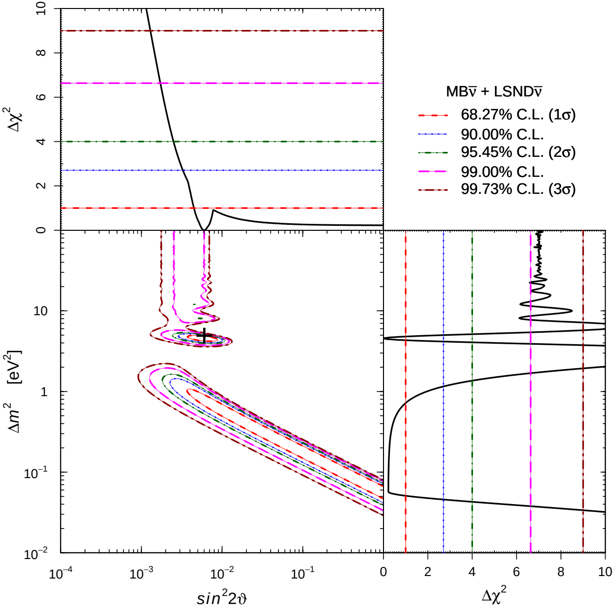
Near Detector at 1.04 km Far Detector at 734 km



[MINOS, Neutrino 2010, 14 June 2010]

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

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



$\chi^2_{\text{min}} = 14.6$

$\text{NdF} = 18$

$\text{GoF} = 69\%$

$\sin^2 2\vartheta = 0.006$

$\Delta m^2 = 4.57\,\text{eV}^2$

Parameter Goodness-of-Fit

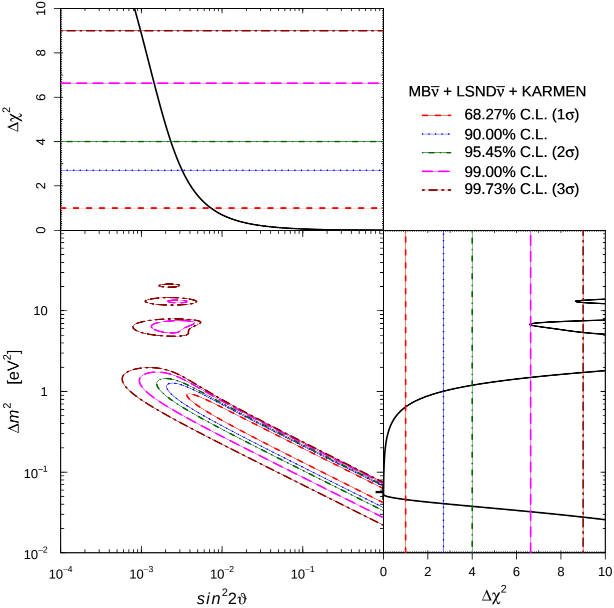
$\Delta\chi^2_{\text{min}} = 1.5$

$\text{NdF} = 2$

$\text{GoF} = 47\%$

[Giunti, Laveder, arXiv:1010.1395]

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



$\chi^2_{\text{min}} = 25.8$

NdF $= 26$

GoF $= 48\%$

$\sin^2 2\vartheta = 1.00$

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

Parameter Goodness-of-Fit

$\Delta\chi^2_{\text{min}} = 6.3$

NdF $= 4$

GoF $= 18\%$

[Giunti, Laveder, arXiv:1010.1395]

# Conservation of Probability

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

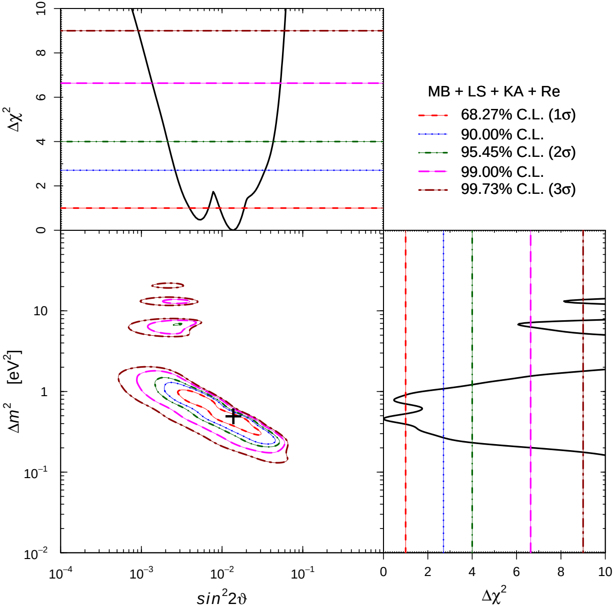
$$P_{\bar{\nu}_e \to \bar{\nu}_e} + P_{\bar{\nu}_\mu \to \bar{\nu}_e} + P_{\bar{\nu}_\tau \to \bar{\nu}_e} + P_{\bar{\nu}_s \to \bar{\nu}_e} = 1$$

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

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

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

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



$\chi^2_{\rm min} = 77.3$

NdF $= 82$

GoF $= 63\%$

$\sin^2 2\vartheta = 0.014$

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

Parameter Goodness-of-Fit

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

NdF $= 2$

GoF $= 22\%$

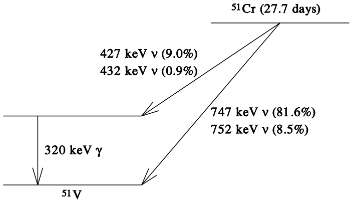
[Giunti, Laveder, arXiv:1010.1395]

# Gallium Anomaly

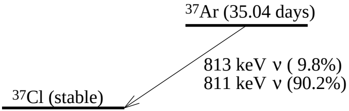
Gallium Radioactive Source Experiments

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

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



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



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

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

[Giunti, Laveder, arXiv:1006.3244]

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

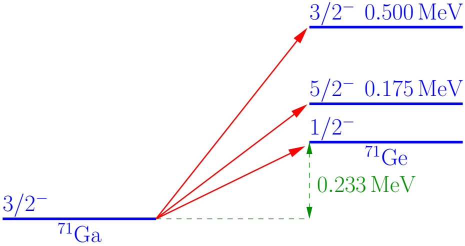
Haxton cross section and uncertainty

[Haxton, PLB 431 (1998) 110, nucl-th/9804011]

- Gallium Anomaly 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]

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

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

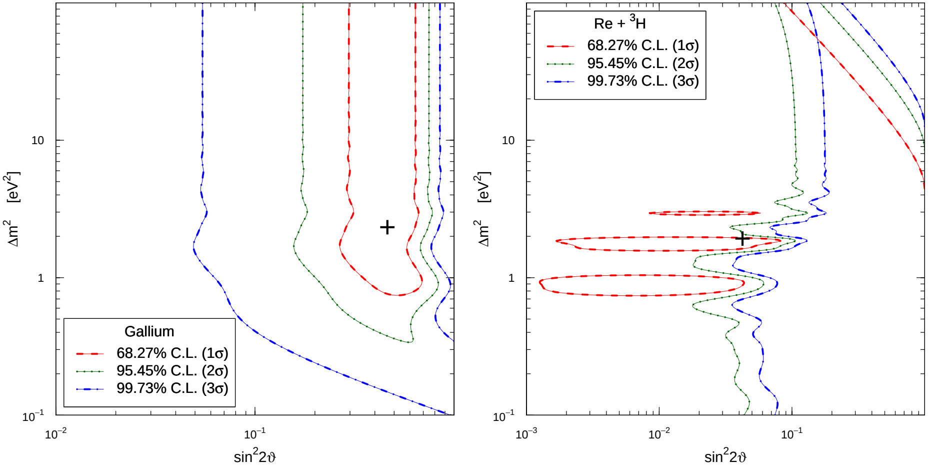
$3\sigma$ upper limit: $\frac{\text{BGT}_{175\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} < 0.056 \times 2 \qquad \frac{\text{BGT}_{500\,\text{keV}}}{\text{BGT}_{\text{G.S.}}} = 0.146 \times 2$

$$\sigma({}^{51}\text{Cr}) = 58.1 \times 10^{-46}\,\text{cm}^2 \left(1^{+0.036}_{-0.028}\right)_{1\sigma}$$

- 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.”

$$\sigma({}^{51}\text{Cr}) = 63.9 \times 10^{-46}\,\text{cm}^2\,(1 \pm 0.106)_{1\sigma}$$



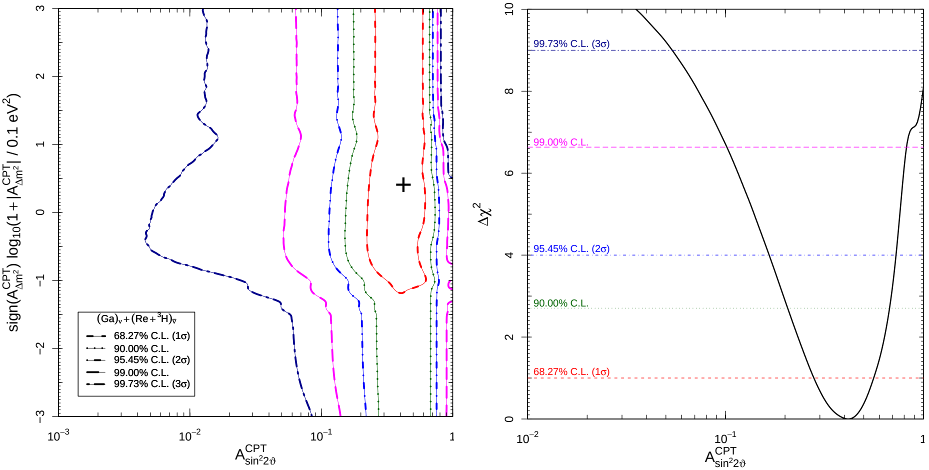
[Giunti, Laveder, arXiv:1006.3244]

[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, arXiv:1008.4750]

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

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

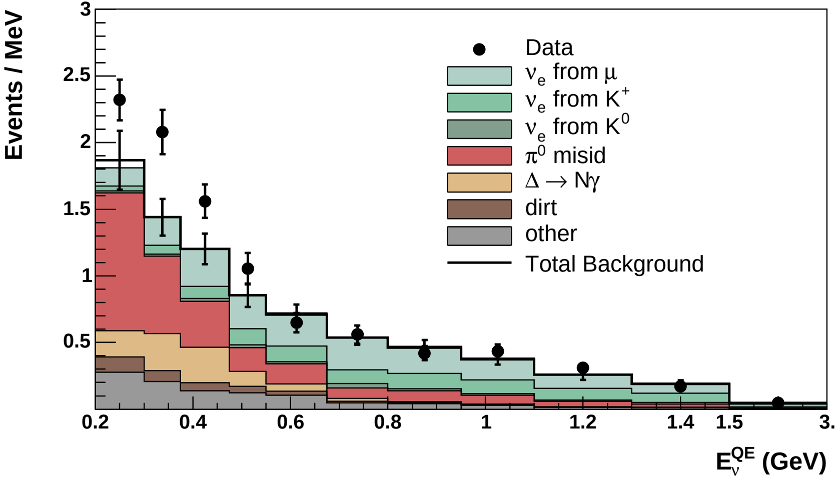
$$A^{CPT}_{\sin^2 2\vartheta} > 0.055 \text{ at } 3\sigma \qquad A^{CPT}_{\sin^2 2\vartheta} > 0 \text{ at } 3.5\sigma.$$

# Conclusions

- Existence of sterile neutrinos is possible
- ΛCDM cosmology and BBN hint at $N_s > 0$
- 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 $\nu_\mu$ disappearance limits
    - Gallium Anomaly ($\nu_e$ disappearance) vs Bugey ($\bar{\nu}_e$ disappearance)
- Interpretation of experimental results is difficult:
    - 3+1 Four-Neutrino Mixing is strongly disfavored (no CP violation)
    - CP violation $\Longrightarrow$ 3+2 Five-Neutrino Mixing or more?
    - CPT violation?
    - . . . ?
- New short-baseline neutrino oscillation experiments are needed!

# Backup Slides

# MiniBooNE Low-Energy Anomaly



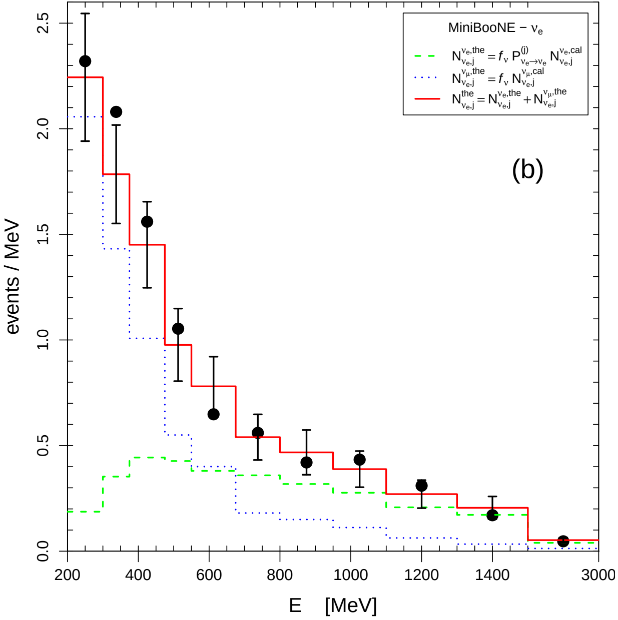
[PRL 102 (2009) 101802, arXiv:0812.2243]

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

[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 $1.21 \pm 0.24$ of detected and predicted charged-current quasi-elastic $\nu_\mu$ events [MiniBooNE, PRL 100 (2008) 032301, arXiv:0706.0926]
- We fit MiniBooNE $\nu_e$ and $\nu_\mu$ data using the info at `http://www-boone.fnal.gov/for_physicists/data_release/lowe/`



No Osc. & $f_\nu = 1$

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

$\text{NdF} = 3 + 16$

$\text{GoF} = 41\%$

Our Hypothesis

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

$\text{NdF} = 16$

$\text{GoF} = 89\%$

$f_\nu = 1.26$

$\sin^2 2\vartheta = 0.32$

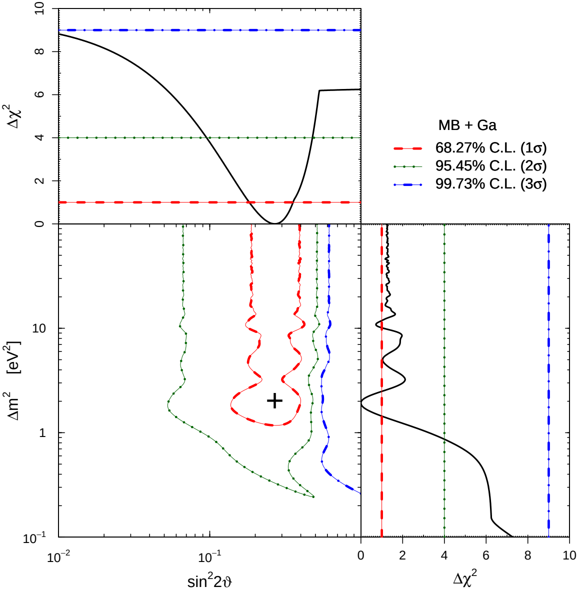
$\Delta m^2 = 1.84\,\text{eV}^2$

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

- Note similar best-fit values of $\sin^2 2\vartheta$ and $\Delta m^2$
- 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



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

$\text{NdF} = 20$

$\text{GoF} = 93\%$

$\sin^2 2\vartheta = 0.27$

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

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