Review on Sterile Neutrinos

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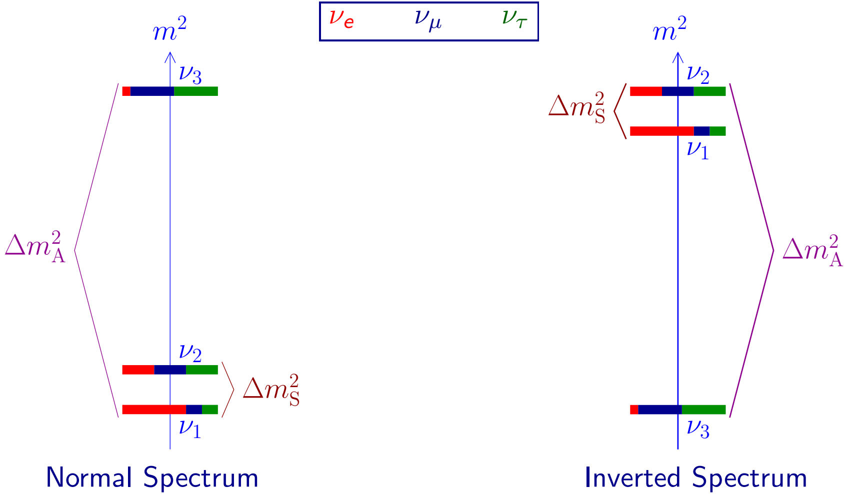
Three-Neutrino Mixing Paradigm



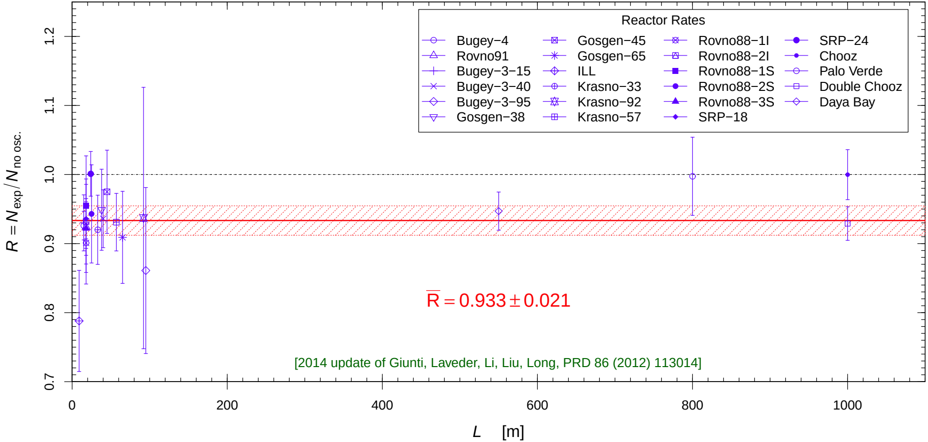
absolute mass scale $\lesssim 1\,\mathrm{eV}$

Indications of SBL Oscillations Beyond 3ν

Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006; update in White Paper, arXiv:1204.5379]

New reactor $\bar{\nu}_e$ fluxes [Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



$\bar{\nu}_e \to \bar{\nu}_e$ $L \simeq 10 - 100\,\mathrm{m}$ $E \simeq 4\,\mathrm{MeV}$

$\sim 3.1\sigma$ deficit $\Delta m^2 \gtrsim 0.5\,\mathrm{eV}^2$ $(\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

[see also: Sinev, arXiv:1103.2452; Ciuffoli, Evslin, Li, JHEP 12 (2012) 110; Zhang, Qian, Vogel, PRD 87 (2013) 073018; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050; Ivanov et al, PRC 88 (2013) 055501]

Gallium Anomaly

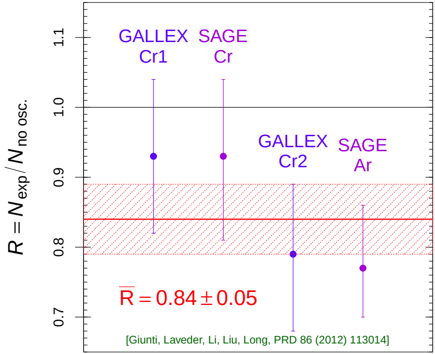
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

Anomaly supported by new ${}^{71}\mathrm{Ga}({}^{3}\mathrm{He}, {}^{3}\mathrm{H}){}^{71}\mathrm{Ge}$ cross section measurement

[Frekers et al., PLB 706 (2011) 134]



$\bar{\nu}_e \to \bar{\nu}_e \qquad E \sim 0.7\,\mathrm{MeV}$

$\langle L \rangle_{\mathrm{GALLEX}} = 1.9\,\mathrm{m}$

$\langle L \rangle_{\mathrm{SAGE}} = 0.6\,\mathrm{m}$

$\sim 2.9\sigma$ anomaly

$\Delta m^2 \gtrsim 1\,\mathrm{eV}^2 \qquad (\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807]

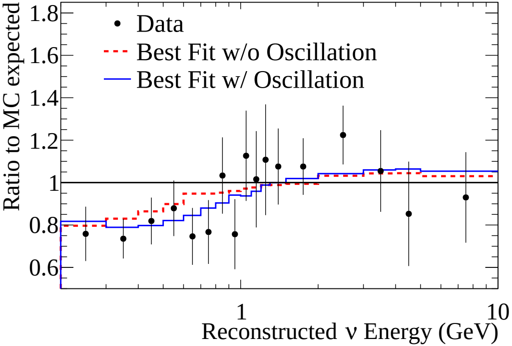
[Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344; MPLA 22 (2007) 2499; PRD 78 (2008) 073009; PRC 83 (2011) 065504]

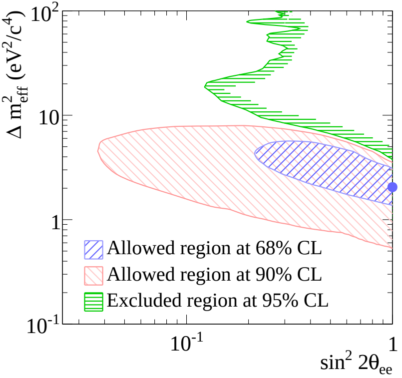
[Mention et al, PRD 83 (2011) 073006]

T2K Near Detector ν_e Disappearance

[arXiv:1410.8811]

$\nu_e \to \nu_e$ $\qquad L \simeq 280\,\text{m}$ $\qquad E \sim 500\,\text{MeV}$





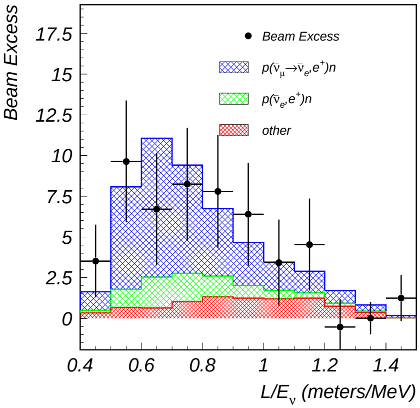
No Oscillations: $\chi^2_{\text{min}}/\text{NDF} = 45.86/51$ $\qquad \Delta\chi^2/\text{NDF} = 3.7/2$

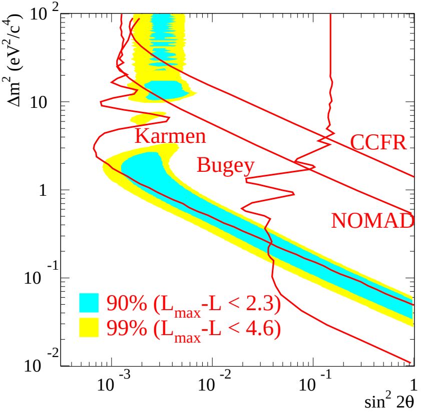
Oscillations: $\chi^2_{\text{min}}/\text{NDF} = 42.16/49$ $\qquad \sim 1.4\sigma$ deviation

LSND

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

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



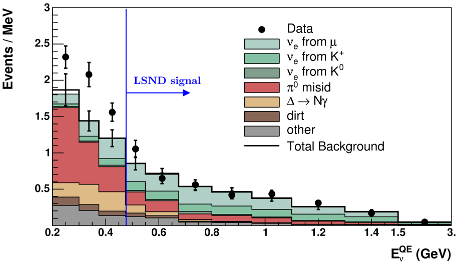


3.8σ excess $\quad \Delta m^2 \gtrsim 0.2\,\mathrm{eV}^2 \quad (\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

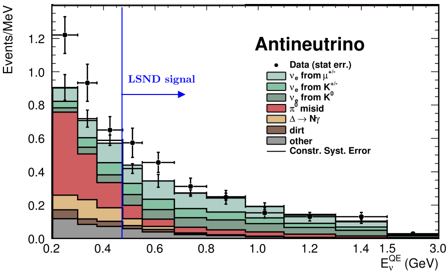
MiniBooNE

$L \simeq 541\,\text{m}$ $\qquad$ $200\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802]



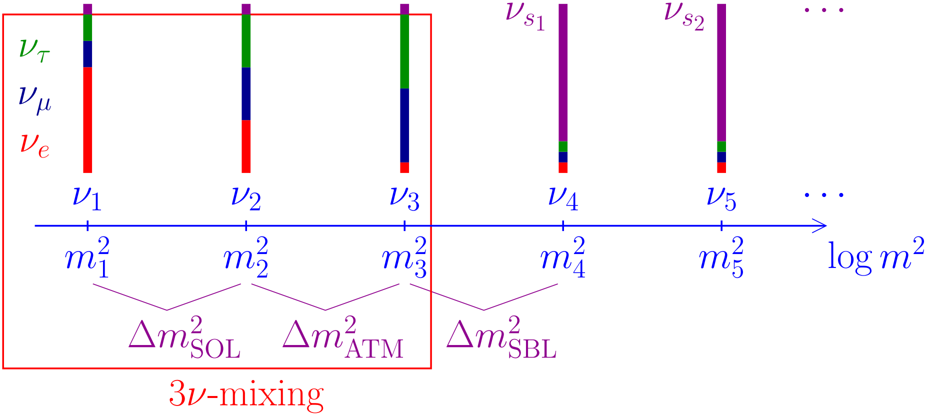
$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- LSND signal: $E > 475\,\text{MeV}$.

- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Terminology: a eV-scale sterile neutrino

means: a eV-scale massive neutrino which is mainly sterile

Sterile Neutrinos from Physics Beyond the SM

- Neutrinos are special in the Standard Model: the only neutral fermions
- In extensions of SM neutrinos can mix with non-SM fermions
- SM doublets: $L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \quad \widetilde{\Phi} = i\sigma_2 \Phi^* = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \xrightarrow[\text{Breaking}]{\text{Symmetry}} \frac{1}{\sqrt{2}} \begin{pmatrix} v \\ 0 \end{pmatrix}$
- SM singlet: $\overline{L_L}\widetilde{\Phi} = \begin{pmatrix} \overline{\nu_L} & \overline{\ell_L} \end{pmatrix} \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} = \overline{\nu_L}\phi^0 + \overline{\ell_L}\phi^- \xrightarrow[\text{Breaking}]{\text{Symmetry}} \frac{v}{\sqrt{2}} \overline{\nu_L}$
- SM singlet $\overline{L_L}\widetilde{\Phi}$ can couple to new singlet (sterile) fermion field ν_R (right-handed neutrino) related to physics beyond the SM
- $\mathcal{L}^{\text{D}} \sim \overline{L_L}\widetilde{\Phi}\nu_R \xrightarrow[\text{Breaking}]{\text{Symmetry}} \frac{v}{\sqrt{2}} \overline{\nu_L}\nu_R$ Dirac mass term
- Surprise: Majorana mass term $\mathcal{L}^{\text{M}} \sim \overline{\nu_R^c}\nu_R$ allowed by SM symmetries
- In general: Dirac mass term $\sim \overline{L_L}\widetilde{\Phi}\nu_R +$ Majorana mass term $\sim \overline{\nu_R^c}\nu_R$
- 3 active $+ N_s$ sterile neutrinos $\Longrightarrow (3 + N_s) \times (3 + N_s)$ mass matrix
- Diagonalization $\Longrightarrow 3 + N_s$ massive Majorana neutrinos

Light Sterile Neutrinos

- Light anti-ν_R are light sterile neutrinos

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

- Sterile means no standard model interactions
  [Pontecorvo, Sov. Phys. JETP 26 (1968) 984]
- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into light sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + 3ν-mixing:

$$\begin{array}{ccccc} & \Delta m^2_{21} \ll & |\Delta m^2_{31}| \ll & |\Delta m^2_{41}| \leq & \ldots \\ \nu_1 & \nu_2 & \nu_3 & \nu_4 & \ldots \\ \nu_e & \nu_\mu & \nu_\tau & \nu_{s_1} & \ldots \end{array}$$

- In this talk I consider sterile neutrinos with mass scale $\sim 1\,\mathrm{eV}$ in light of short-baseline Reactor Anomaly, Gallium Anomaly, LSND.

- Other possibilities (not incompatible):

  - Very light sterile neutrinos with mass scale $\ll 1\,\mathrm{eV}$: important for solar neutrino phenomenology

    [Das, Pulido, Picariello, PRD 79 (2009) 073010]

    [de Holanda, Smirnov, PRD 83 (2011) 113011]

    Recent Daya Bay constraits for $10^{-3} \lesssim \Delta m^2 \lesssim 10^{-1}\,\mathrm{eV}^2$

    [PRL 113 (2014) 141802, arXiv:1407.7259]

  - Heavy sterile neutrinos with mass scale $\gg 1\,\mathrm{eV}$: could be Warm Dark Matter

    [Kusenko, Phys. Rept. 481 (2009) 1]

    [Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191]

    [Drewes, IJMPE, 22 (2013) 1330019]

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

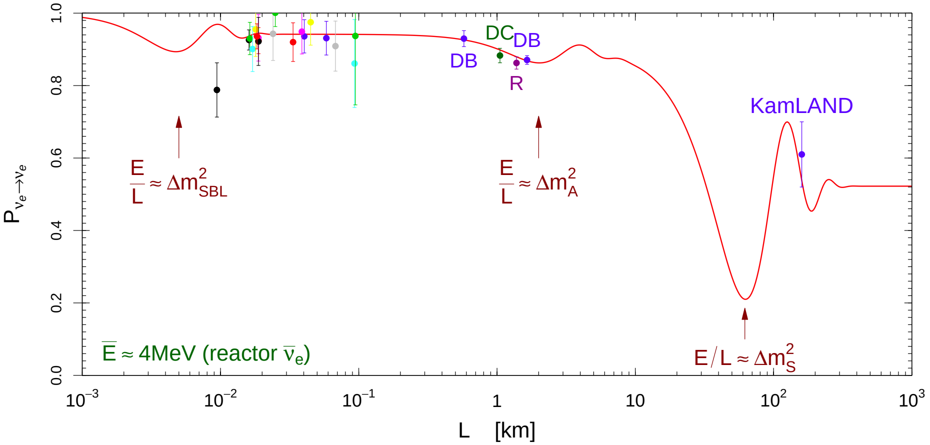
Perturbation of 3ν Mixing: $|U_{e4}|^2 \ll 1\,,\ |U_{\mu 4}|^2 \ll 1\,,\ |U_{\tau 4}|^2 \ll 1\,,\ |U_{s4}|^2 \simeq 1$

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

SBL

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

but CP violation is not observable in SBL experiments!



$$P^{LBL}_{\overset{(-)}{\nu_e}\to\overset{(-)}{\nu_e}} \simeq 1 - \frac{1}{2}\sin^2 2\vartheta_{14} - \cos^4\vartheta_{14}\sin^2 2\vartheta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

3+1: Appearance vs 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:

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

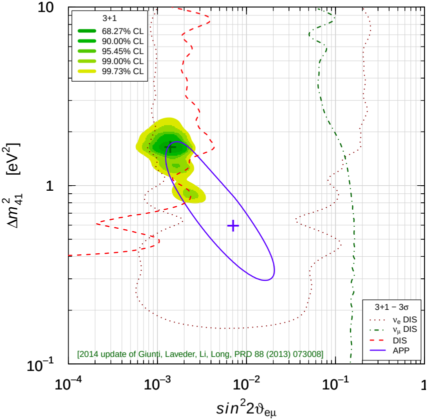
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ $\Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

- Similar constraint in 3+2, 3+3, ..., 3+N_s !

Global 3+1 Fit

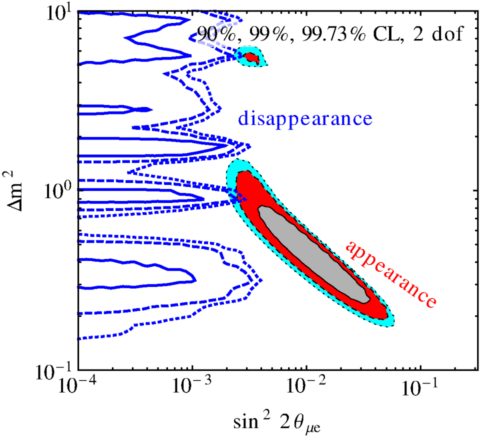
Our Fit



GoF = 5%

PGoF = 0.1%

Kopp, Machado, Maltoni, Schwetz

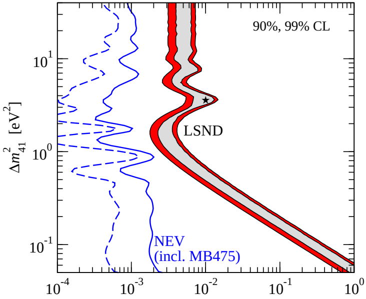


GoF = 19%

PGoF = 0.01%

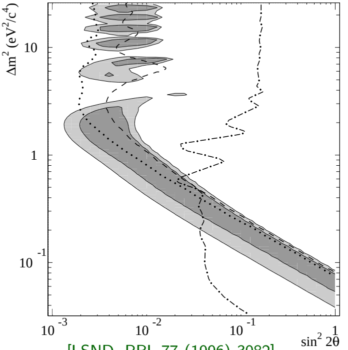
[Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

Different LSND Treatments



$\leftarrow$ Kopp, Machado, Maltoni, Schwetz

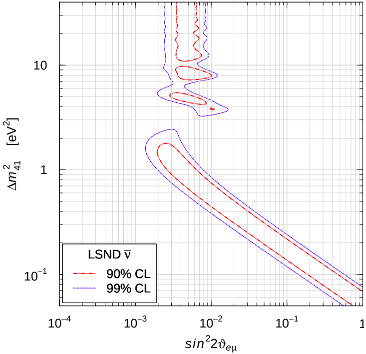
[Maltoni, Schwetz, PRD 76 (2007) 093005]



[LSND, PRL 77 (1996) 3082]

only $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ decay at rest data

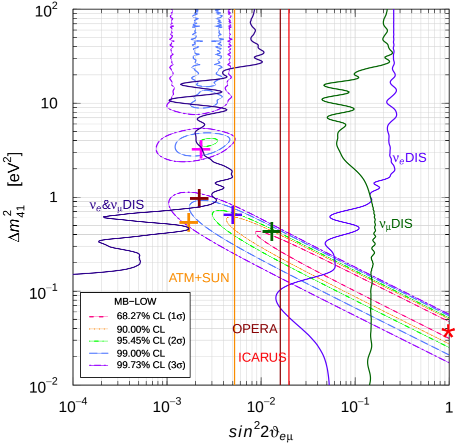
$20 < E_{e^+} < 60\,\text{MeV}$

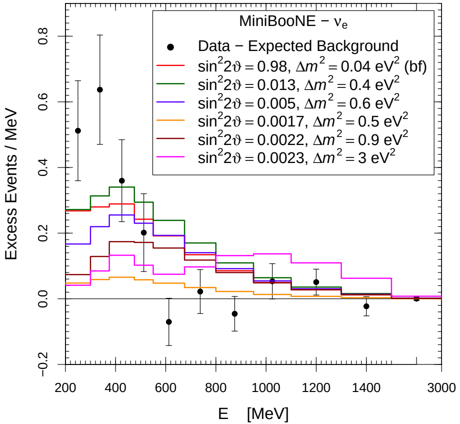


$\leftarrow$ Our Fit

[improvement of Giunti, Laveder, PRD 82 (2010) 093016]

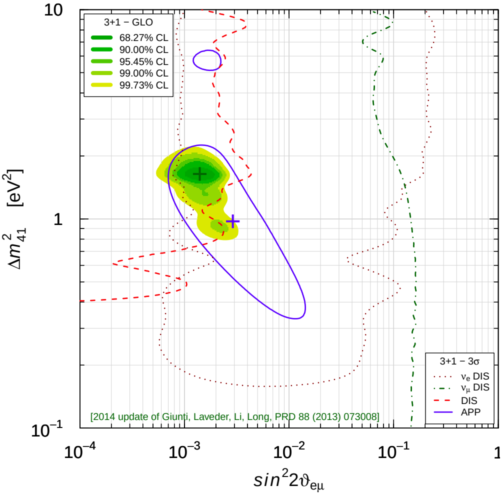
MiniBooNE Low-Energy Excess?





- No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 5 \times 10^{-3}$
- APP-DIS PGoF $= 0.1\%$
- Neutrino energy reconstruction problem? [Martini, Ericson, Chanfray, PRD 87 (2013) 013009]
- Pragmatic Approach: discard the Low-Energy Excess because it is very likely not due to oscillations

Pragmatic 3+1 Fit



MiniBooNE $E > 475\,\text{MeV}$

GoF $= 26\%$ PGoF $= 7\%$

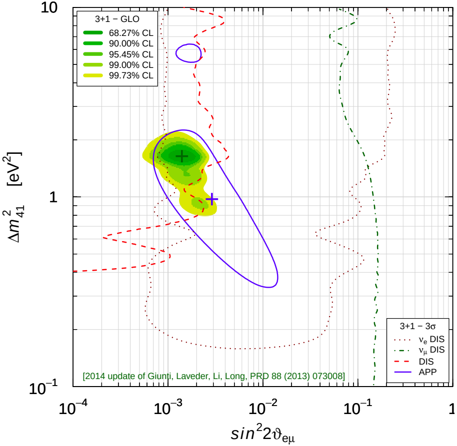
- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND ($\nu_s$), MiniBooNE (?), OPERA ($\cancel{\nu_s}$), ICARUS ($\cancel{\nu_s}$), KARMEN ($\cancel{\nu_s}$), NOMAD ($\cancel{\nu_s}$), BNL-E776 ($\cancel{\nu_s}$)
- DIS ν_e & $\bar{\nu}_e$: Reactors (ν_s), Gallium (ν_s), ν_eC ($\cancel{\nu_s}$), Solar ($\cancel{\nu_s}$)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW ($\cancel{\nu_s}$), MINOS ($\cancel{\nu_s}$), Atmospheric ($\cancel{\nu_s}$), MiniBooNE/SciBooNE ($\cancel{\nu_s}$)

No Osc. disfavored at 6.3σ

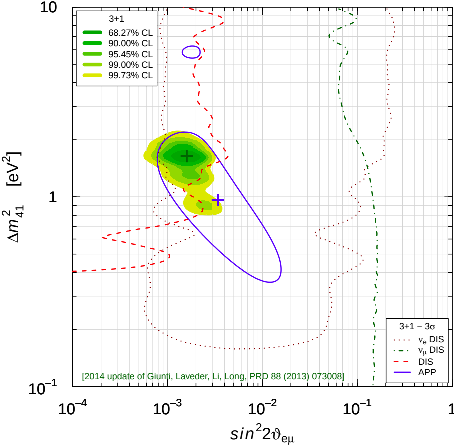
$\Delta\chi^2/\text{NDF} = 47.7/3$

MiniBooNE Impact in Pragmatic 3+1 Fit?

with MiniBooNE



without MiniBooNE



with MiniBooNE	without MiniBooNE
GoF = 26% PGoF = 7%	GoF = 16% PGoF = 5%
No Osc. disfavored at 6.3σ	No Osc. disfavored at 6.4σ
$\Delta\chi^2/\mathrm{NDF} = 47.7/3$	$\Delta\chi^2/\mathrm{NDF} = 48.1/3$

Without LSND: No Osc. disfavored only at 2.6σ $(\Delta\chi^2/\mathrm{NDF} = 11.4/3)$

Effective SBL Oscillation Probabilities in 3+2 Schemes

$$\phi_{kj} = \Delta m^2_{kj} L / 4E$$

$$\eta = \arg[U^*_{e4} U_{\mu4} U_{e5} U^*_{\mu5}]$$

$$P_{\overset{(-)}{\nu}_{\mu} \to \overset{(-)}{\nu}_{e}} = 4|U_{e4}|^2 |U_{\mu4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu5}|^2 \sin^2\phi_{51} + 8|U_{\mu4} U_{e4} U_{\mu5} U_{e5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} \overset{(+)}{-} \eta)$$

$$P_{\overset{(-)}{\nu}_{\alpha} \to \overset{(-)}{\nu}_{\alpha}} = 1 - 4(1 - |U_{\alpha4}|^2 - |U_{\alpha5}|^2)(|U_{\alpha4}|^2 \sin^2\phi_{41} + |U_{\alpha5}|^2 \sin^2\phi_{51}) - 4|U_{\alpha4}|^2|U_{\alpha5}|^2 \sin^2\phi_{54}$$

[Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004; Maltoni, Schwetz, PRD 76 (2007) 093005; Karagiorgi et al, PRD 80 (2009) 073001; Kopp, Maltoni, Schwetz, PRL 107 (2011) 091801; Giunti, Laveder, PRD 84 (2011) 073008; Donini et al, JHEP 07 (2012) 161; Archidiacono et al, PRD 86 (2012) 065028; Conrad et al, AHEP 2013 (2013) 163897; Archidiacono et al, PRD 87 (2013) 125034; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050; Giunti, Laveder, Y.F. Li, H.W. Long, PRD 88 (2013) 073008; Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]

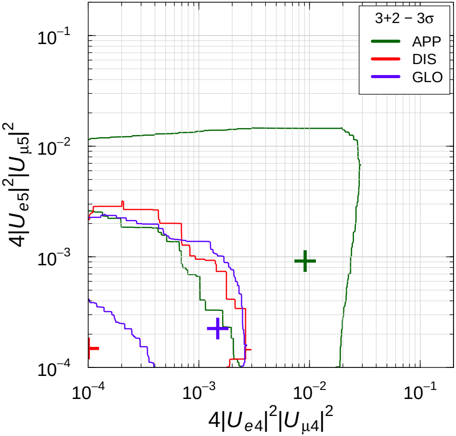
- Good: CP violation
- Bad: Two massive sterile neutrinos at the eV scale!

  4 more parameters: $\underbrace{\Delta m^2_{41}, |U_{e4}|^2, |U_{\mu4}|^2}_{3+1}, \Delta m^2_{51}, |U_{e5}|^2, |U_{\mu5}|^2, \eta$

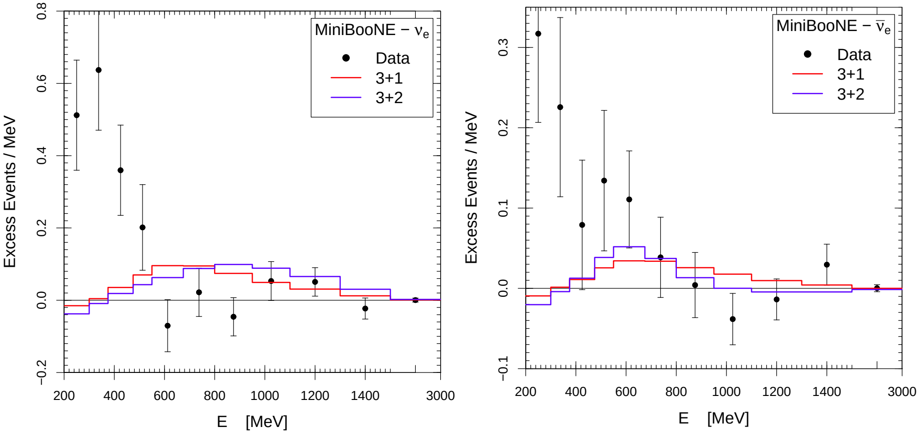
Global Fits	Our Fit		KMMS	
	3+1	3+2	3+1	3+2
GoF	5%	7%	19%	23%
PGoF	0.1%	0.05%	0.01%	0.003%

- Our Fit: 2014 update of Giunti, Laveder, Li, Long, PRD 88 (2013) 073008
- KMMS: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050

APP-DIS 3+2 Tension:



3+2 cannot fit MiniBooNE Low-Energy Excess



- Note difference between 3+2 ν_e and $\bar{\nu}_e$ histograms due to CP violation
- 3+2 can fit slightly better the small $\bar{\nu}_e$ excess at about 600 MeV
- 3+2 fit of low-energy excess as bad as 3+1
- Claims that 3+2 can fit low-energy excess do not take into account constraints from other data

No need of 3+2

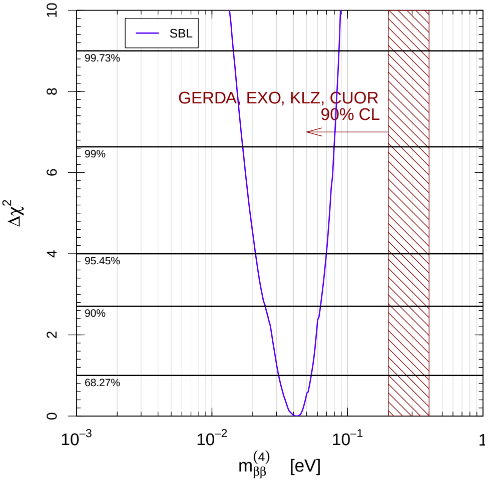
- 3+2 should be preferred to 3+1 only if
  - there is evidence of two peaks of the probability corresponding to two Δm^2's

    or
  - there is CP-violating difference of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions
- final ν_e + 2010 $\bar{\nu}_e$ MiniBooNE data indicated ν_e–$\bar{\nu}_e$ difference

  $\Downarrow$

  reasonable and useful to consider 3+2
- ν_e–$\bar{\nu}_e$ difference almost disappeared with 2012 final MiniBooNE $\bar{\nu}_e$ data
- 3+2 cannot fit the low-energy excess (as 3+1)
- PGoF of 3+2 is even worse than that of 3+1!
- 3+2 has more tension with cosmological data than 3+1
- Conclusion: forget 3+2! (at least until new data require it)

Neutrinoless Double-β Decay



[Giunti, Laveder, Li, Long, 2014]

Pragmatic 3+1 Fit

$$|m_{\beta\beta}| = \left| \sum_{k=1}^{4} U_{ek}^2 \, m_k \right|$$

$$m_{\beta\beta}^{(4)} = |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

caveat:

possible cancellation with $m_{\beta\beta}^{(3\nu-IH)}$

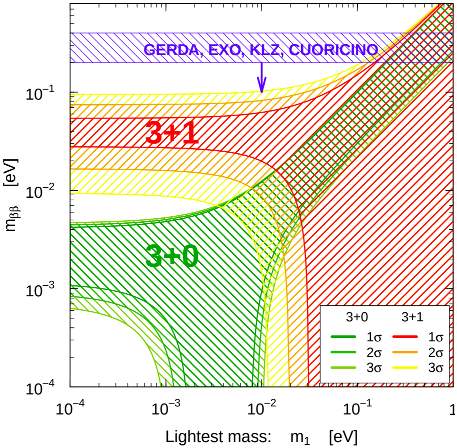
[Barry et al, JHEP 07 (2011) 091]

[Li, Liu, PLB 706 (2012) 406]

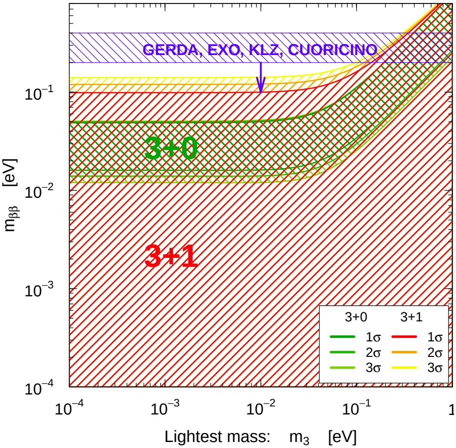
[Rodejohann, JPG 39 (2012) 124008]

[Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]

Normal 3ν Spectrum



Inverted 3ν Spectrum



[Giunti, Laveder, Li, Long, 2014]

Conclusions

- Short-Baseline ν_e and $\bar{\nu}_e$ Disappearance:
  - Experimental data agree on Reactor $\bar{\nu}_e$ and Gallium ν_e anomalies.
  - Problem: systematic uncertainties.
  - Many promising projects to test unambiguously short-baseline ν_e and $\bar{\nu}_e$ disappearance in a few years with reactors and radioactive sources.
  - Independent tests through effect of m_4 in β-decay and $\beta\beta_{0\nu}$-decay.

- Short-Baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ LSND Signal:
  - Not seen by other SBL $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ experiments.
  - MiniBooNE experiment has been inconclusive.
  - Experiments with near detector are needed to check LSND signal!
  - If $|U_{e4}| > 0$ why not $|U_{\mu 4}| > 0$? $\Longrightarrow$ $\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 > 0$

- Pragmatic 3+1 Fit is fine: moderate APP-DIS tension.

- 3+2 is not needed: same APP-DIS tension as 3+1 and no evidence of CP violation.