Sterile Neutrinos - Review

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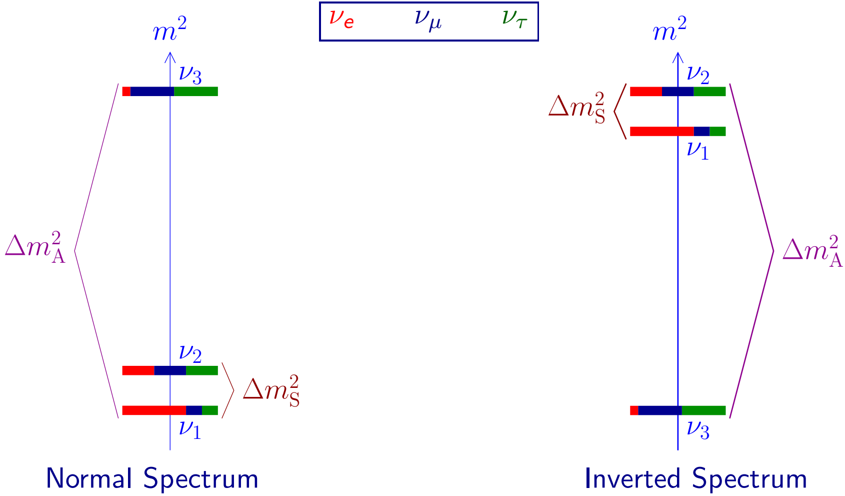
15th International Workshop on Next Generation
Nucleon Decay and Neutrino Detectors

APC, Paris

4-6 November 2014

Three-Neutrino Mixing Paradigm



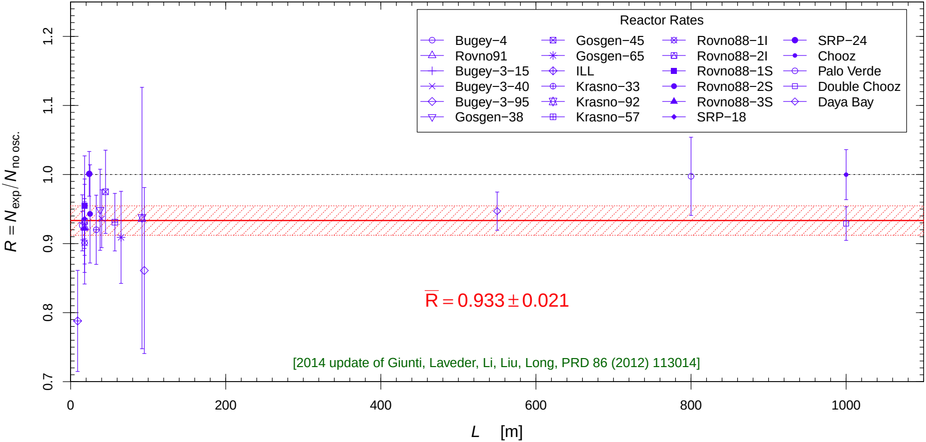
absolute mass scale $\lesssim 1\,\mathrm{eV}$

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

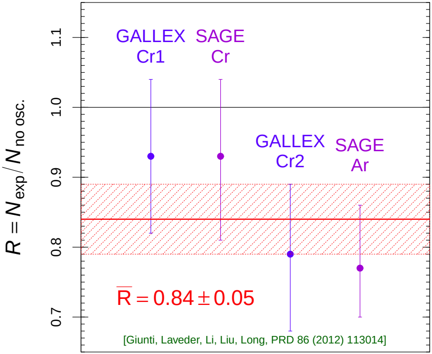
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

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

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



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

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

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

$\sim 2.9\sigma$ anomaly

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

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

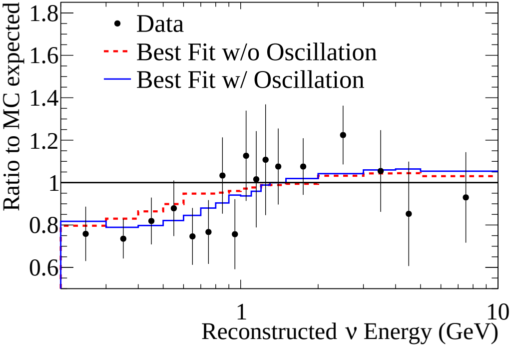
[Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344; MPLA 22 (2007) 2499; PRD 78 (2008) 073009; PRC 83 (2011) 065504]

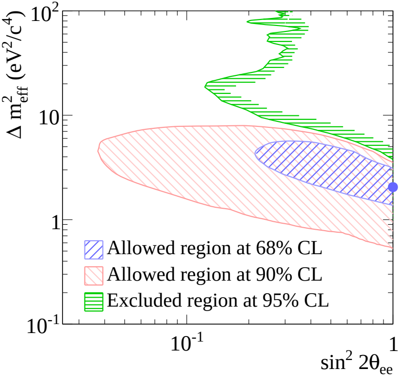
[Mention et al, PRD 83 (2011) 073006]

T2K Near Detector ν_e Disappearance

[arXiv:1410.8811]

$\nu_e \to \nu_e$ $\quad$ $L \simeq 280\,\mathrm{m}$ $\quad$ $E \sim 500\,\mathrm{MeV}$





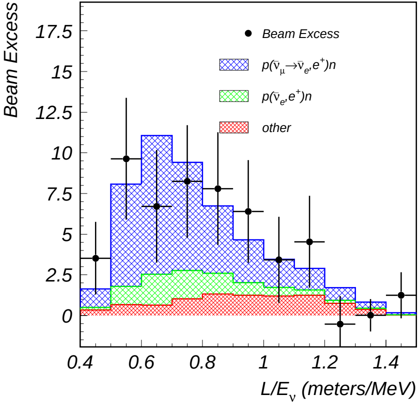
No Oscillations: $\chi^2_{\mathrm{min}}/\mathrm{NDF} = 45.86/51$ $\quad$ $\Delta\chi^2/\mathrm{NDF} = 3.7/2$

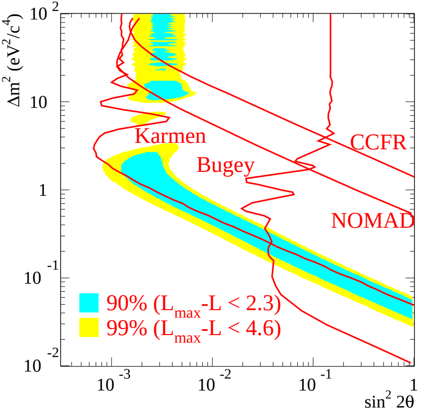
Oscillations: $\chi^2_{\mathrm{min}}/\mathrm{NDF} = 42.16/49$ $\quad$ $\sim 1.4\sigma$ anomaly

LSND

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

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



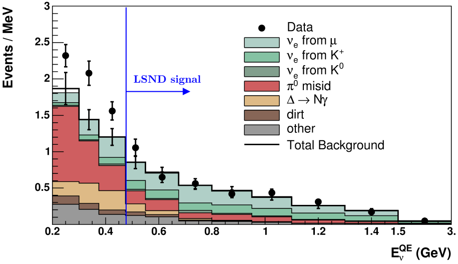


3.8σ excess $\quad \Delta m^2 \gtrsim 0.2\,\mathrm{eV}^2 \quad (\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

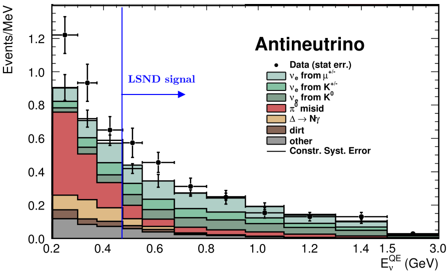
MiniBooNE

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

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



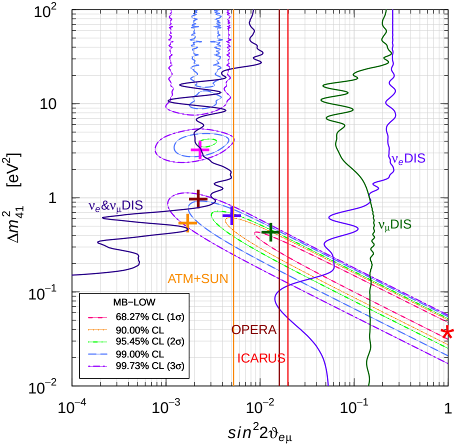
$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]

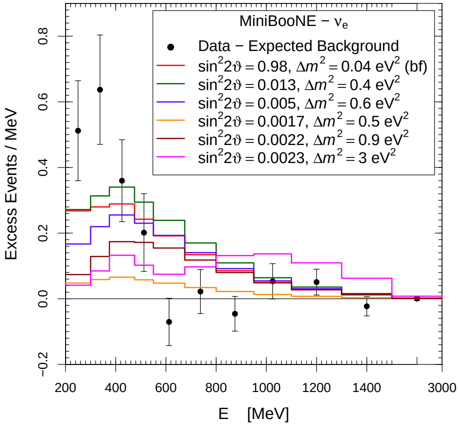


- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- LSND signal: $E > 475\,\text{MeV}$.

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

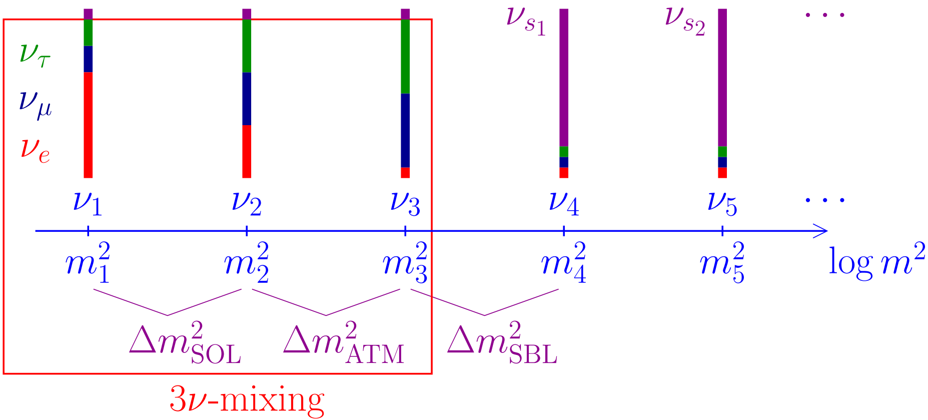
MiniBooNE Low-Energy Excess?





- 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]
- Our approach: discard the Low-Energy Excess because it is very likely not due to oscillations

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Light Sterile Neutrinos

- Physics Beyond the SM $\Longrightarrow$ right-handed sterile neutrinos
- 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 $\sim 1\,\text{eV}$ in light of short-baseline Reactor Anomaly, Gallium Anomaly, LSND.
- Other possibilities (not incompatible):
  - Very light sterile neutrinos with mass scale $\ll 1\,\text{eV}$: important for solar neutrino phenomenology

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

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

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

    [PRL 113 (2014) 141802, arXiv:1407.7259]
  - Heavy sterile neutrinos with mass scale $\gg 1\,\text{eV}$: 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

$$P^{\mathrm{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha4}|^2 |U_{\beta4}|^2$$

$$P^{\mathrm{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha4}|^2 \left(1 - |U_{\alpha4}|^2\right)$$

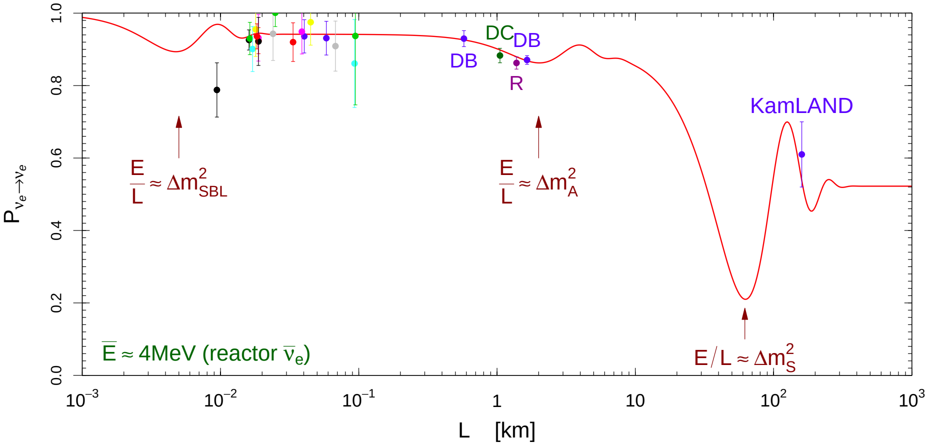
Perturbation of 3ν Mixing: $|U_{e4}|^2 \ll 1\,,\ |U_{\mu4}|^2 \ll 1\,,\ |U_{\tau4}|^2 \ll 1\,,\ |U_{s4}|^2 \simeq 1$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

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

but CP violation is not observable in SBL experiments!



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

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:

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

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

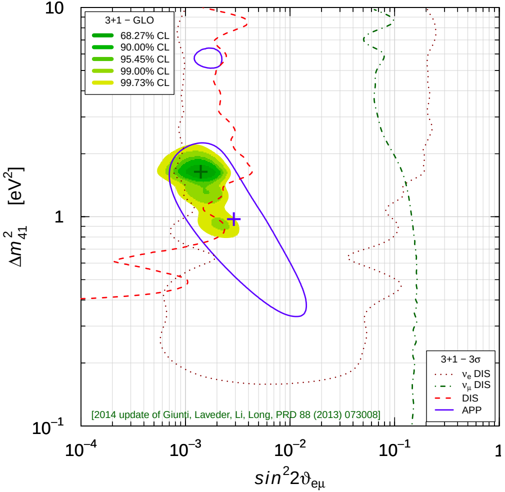
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

- 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, IJMPA 12 (1997) 3669-3694; Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

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

3+1 Global Fit



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

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 ($\cancel{\nu_s}$)

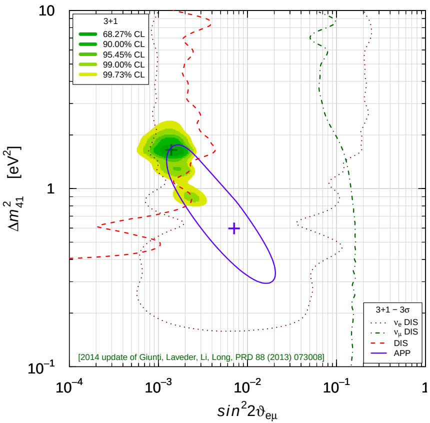
No Osc. disfavored at 6.3σ

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

[different approach and conclusions: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

All MiniBooNE Data?

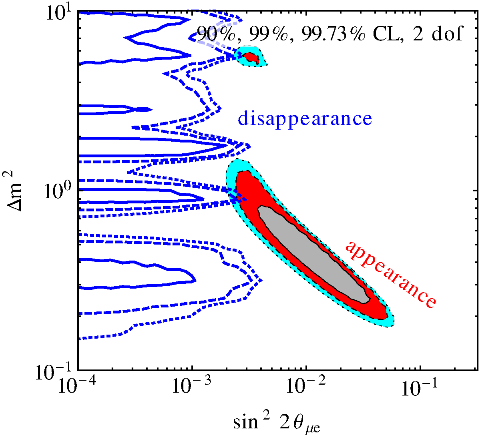
Our Fit



GoF = 5%

PGoF = 0.1%

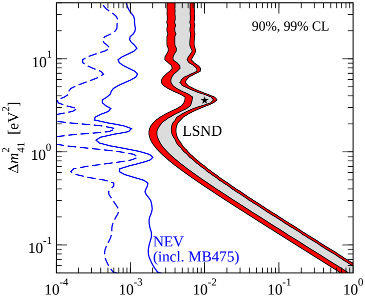
Kopp, Machado, Maltoni, Schwetz



GoF = 19%

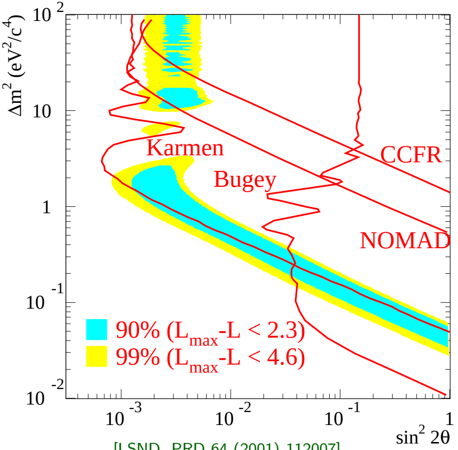
PGoF = 0.01%

∼ Different LSND Treatments ∼

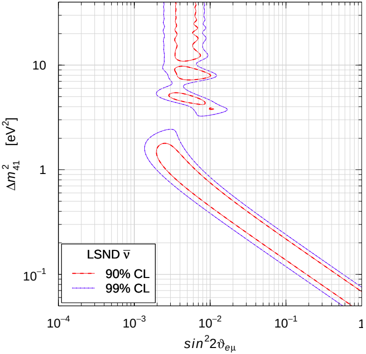


← Kopp, Machado, Maltoni, Schwetz

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



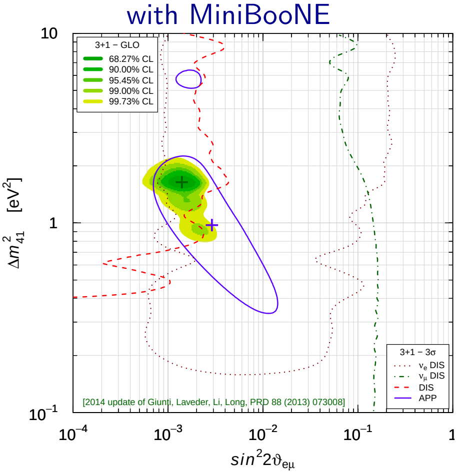
[LSND, PRD 64 (2001) 112007]

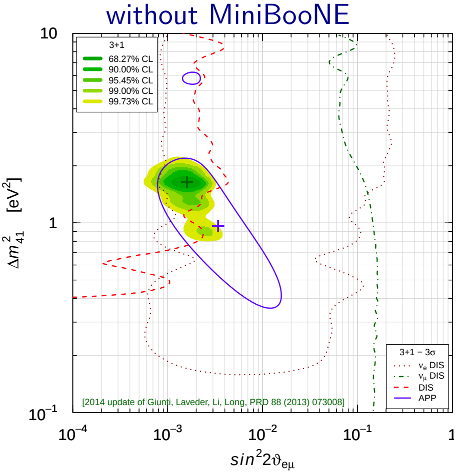


← Our Fit

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

MiniBooNE Impact on SBL Oscillations?





GoF = 26% PGoF = 7%

No Osc. disfavored at 6.3σ

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

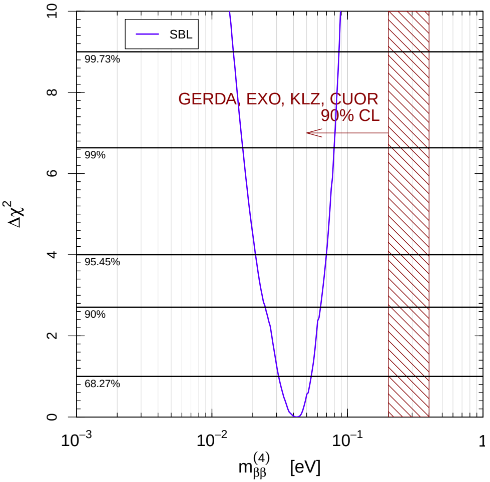
GoF = 16% PGoF = 5%

No Osc. disfavored at 6.4σ

$\Delta\chi^2/\mathrm{NDF} = 48.1/3$

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

Neutrinoless Double-β Decay



[Giunti, Laveder, Li, Long, 2014]

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

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

caveat:

possible cancellation

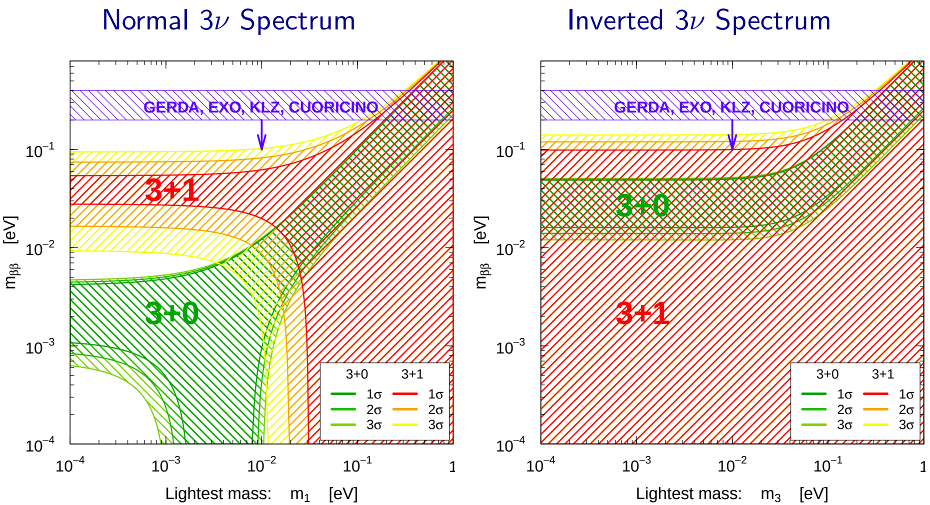
with $m_{\beta\beta}^{(3\nu-IH)}$

[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]



[Giunti, Laveder, Li, Long, 2014]

Conclusions

- Short-Baseline ν_e and $\bar{\nu}_e$ 3+1 Disappearance:
  - Experimental data agree on Reactor $\bar{\nu}_e$ and Gallium ν_e anomalies.
  - Problem: systematic uncertainties.
  - Interesting recent T2K hint of possible SBL ν_e disappearance.
  - 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 $|U_{\mu4}| > 0$? $\Longrightarrow$ $\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 > 0$