

Phenomenology of Light Sterile Neutrinos

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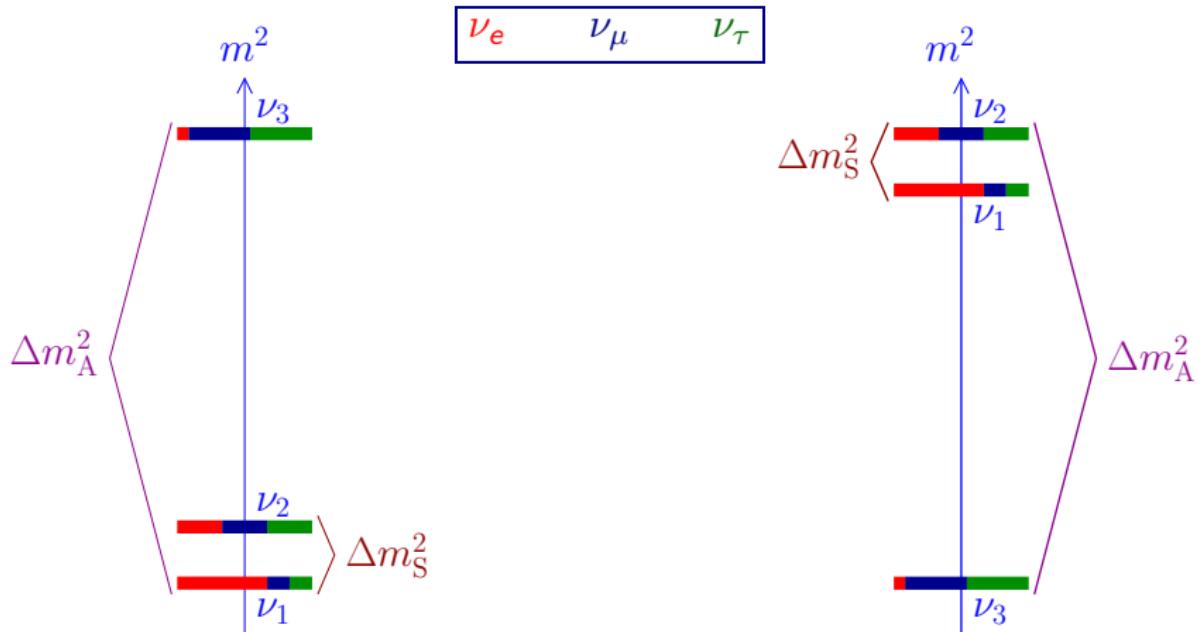
DISCRETE 2014

Fourth Symposium on Prospects in the Physics of Discrete Symmetries

King's College, London, UK

2-6 December 2014

Three-Neutrino Mixing Paradigm



absolute mass scale $\lesssim 1 \text{ eV}$

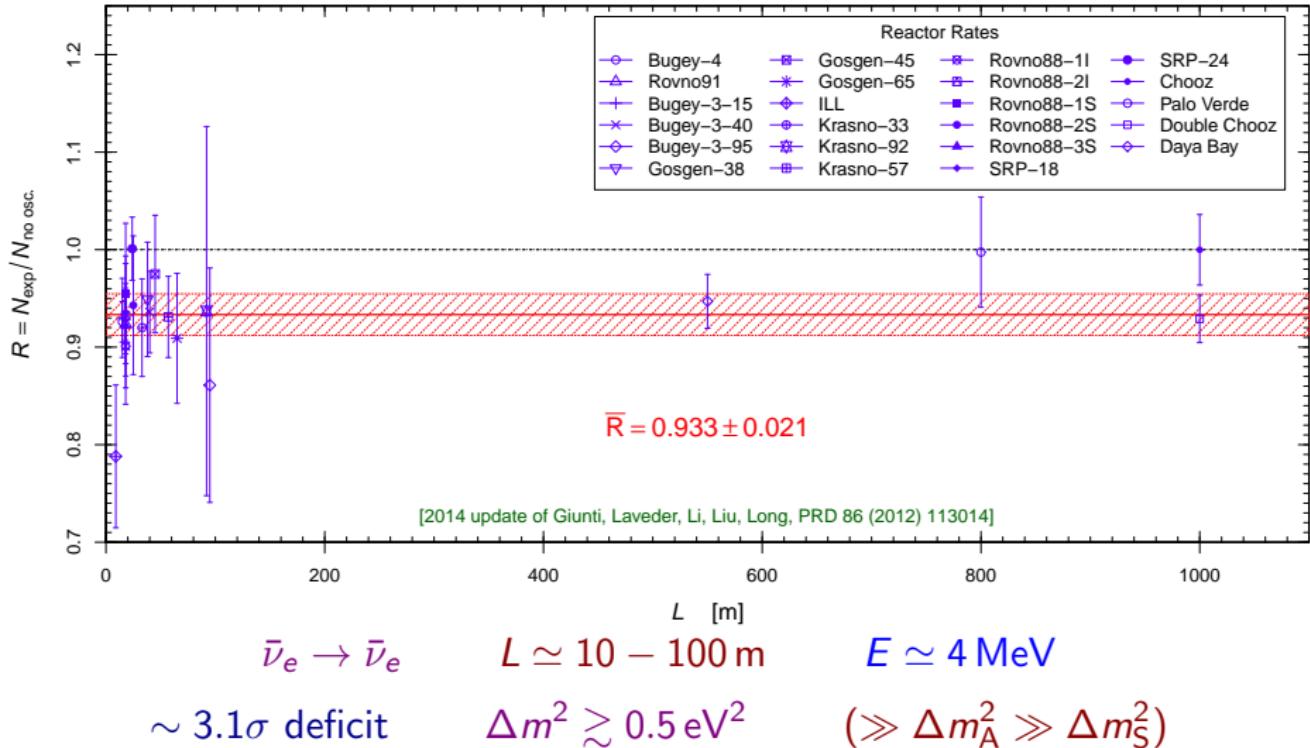
Indications of SBL Oscillations Beyond 3ν

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]



[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

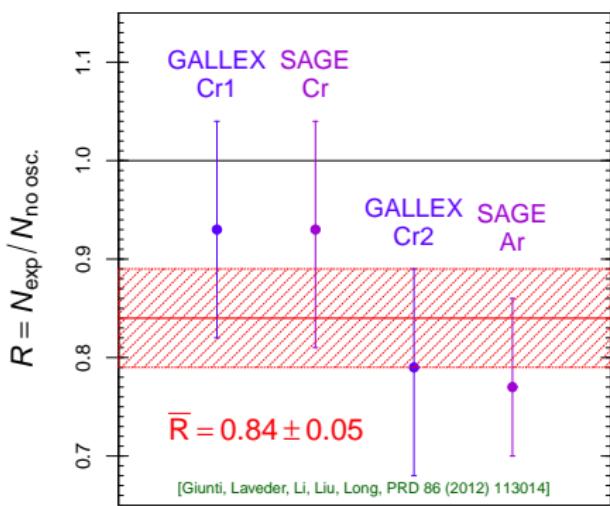
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

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]



$\bar{\nu}_e \rightarrow \bar{\nu}_e$ $E \sim 0.7 \text{ MeV}$

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

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

$\sim 2.9\sigma$ anomaly

$$\Delta m^2 \gtrsim 1 \text{ eV}^2 \quad (\gg \Delta m_A^2 \gg \Delta m_S^2)$$

[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]

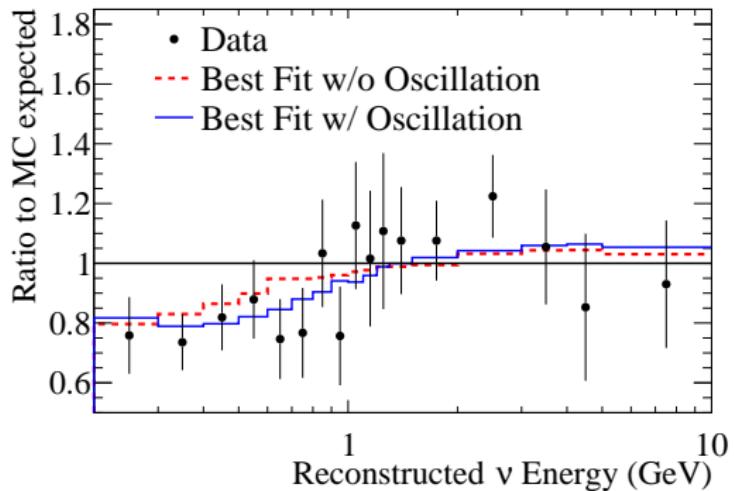
T2K Near Detector ν_e Disappearance

[arXiv:1410.8811]

$$\nu_e \rightarrow \nu_e$$

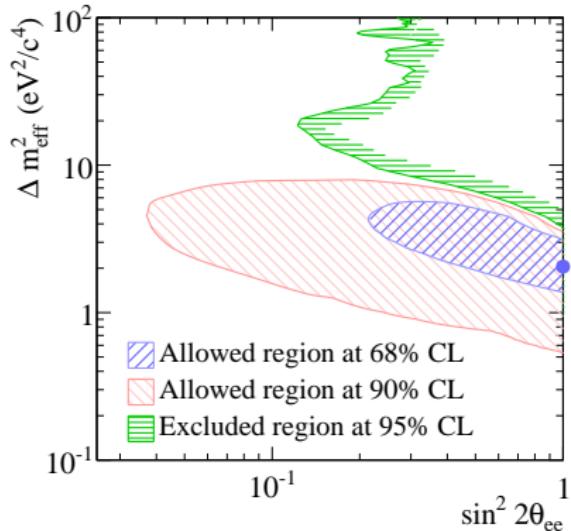
$$L \simeq 280 \text{ m}$$

$$E \sim 500 \text{ MeV}$$



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

Oscillations: $\chi^2_{\min}/\text{NDF} = 42.16/49$



$\Delta\chi^2/\text{NDF} = 3.7/2$

$\sim 1.4\sigma$ deviation

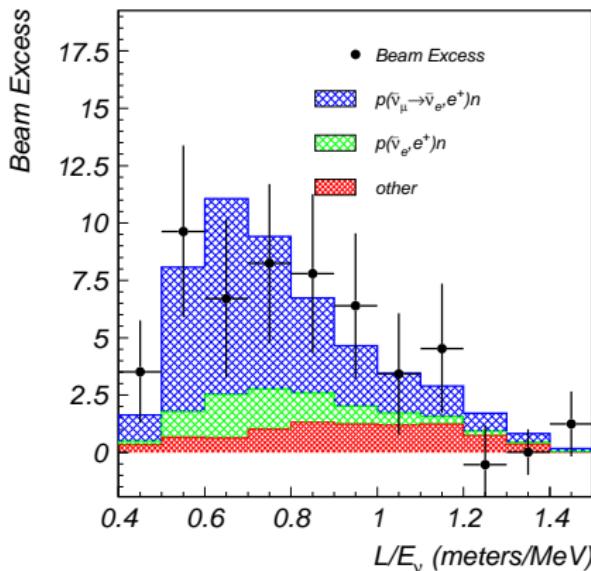
LSND

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

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

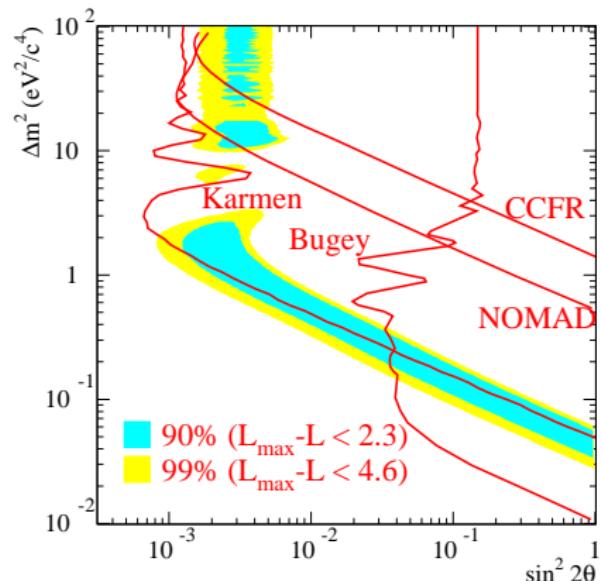
$$L \simeq 30 \text{ m}$$

$$20 \text{ MeV} \leq E \leq 200 \text{ MeV}$$



3.8σ excess

$$\Delta m^2 \gtrsim 0.2 \text{ eV}^2 \quad (\gg \Delta m_A^2 \gg \Delta m_S^2)$$



MiniBooNE

$L \simeq 541 \text{ m}$

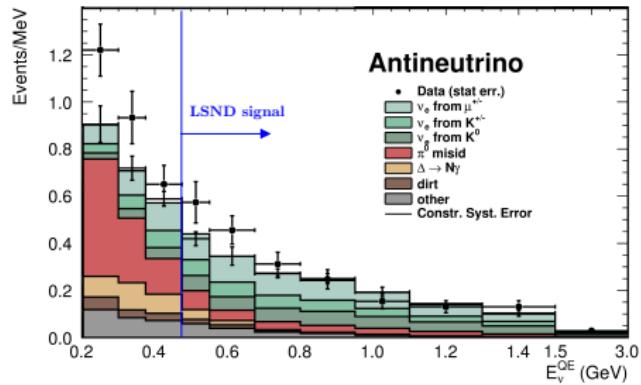
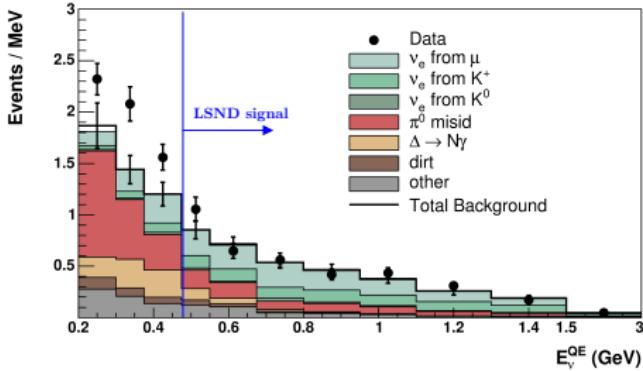
$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$

$$\nu_\mu \rightarrow \nu_e$$

[PRL 102 (2009) 101802]

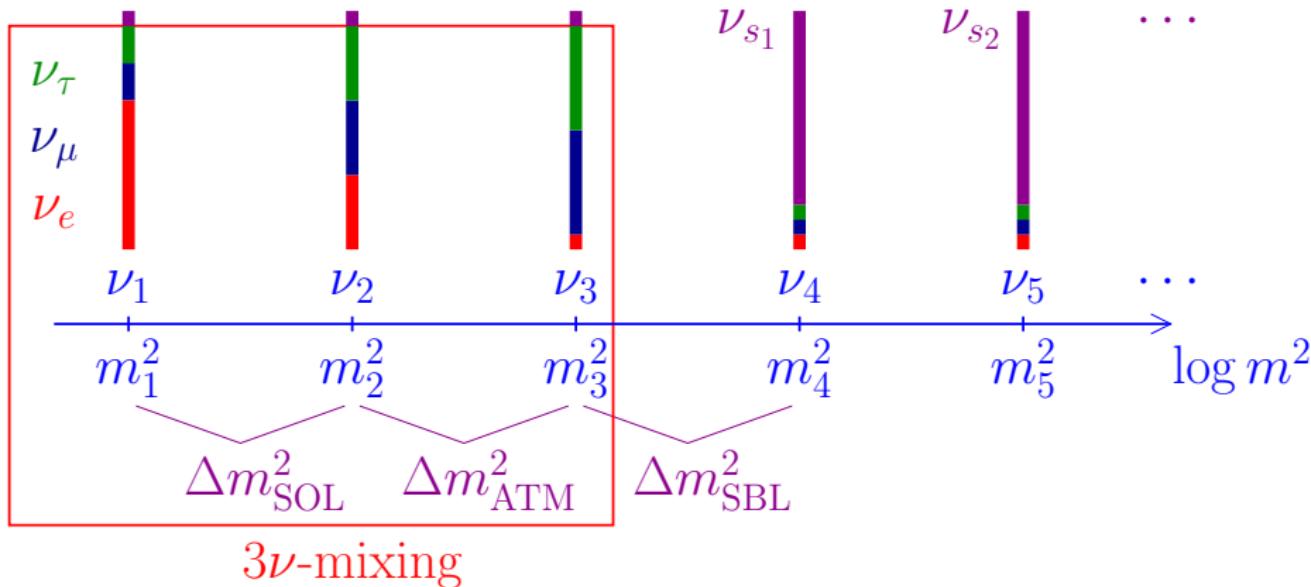
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

[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

Light Sterile Neutrinos

- ▶ Physics Beyond the SM \iff Sterile Neutrinos
- ▶ Sterile means no standard model interactions
[Pontecorvo, Sov. Phys. JETP 26 (1968) 984]
- ▶ Active neutrinos (ν_e, ν_μ, ν_τ) 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:

$$\Delta m_{21}^2 \ll |\Delta m_{31}^2| \ll |\Delta m_{41}^2| \leq \dots$$

ν_1	ν_2	ν_3	ν_4	\dots
ν_e	ν_μ	ν_τ	ν_{s1}	\dots

- ▶ 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 constraints 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

$$P_{\nu_\alpha \rightarrow \nu_\beta}^{\text{SBL}} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

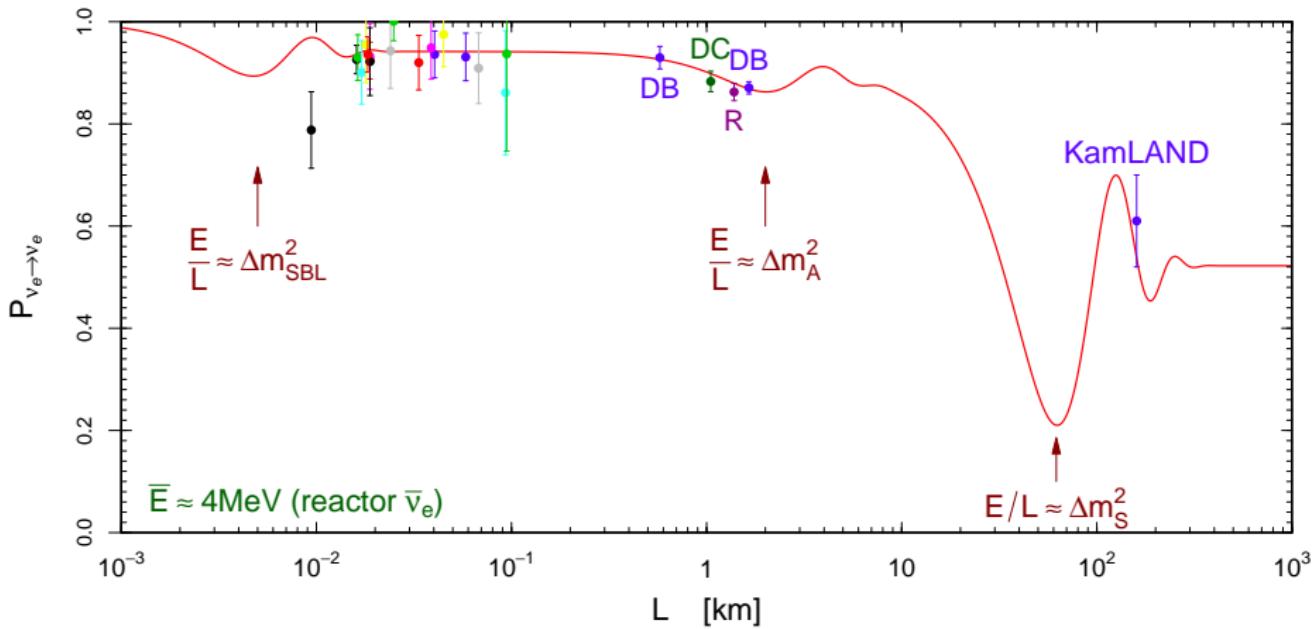
$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

$$P_{\nu_\alpha \rightarrow \nu_\alpha}^{\text{SBL}} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

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

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





$$P_{\nu_e \rightarrow \nu_e}^{\text{LBL}} \simeq 1 - \frac{1}{2} \sin^2 2\vartheta_{14} - \cos^4 \vartheta_{14} \sin^2 2\vartheta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

3+1: Appearance vs Disappearance

- ν_e disappearance experiments:

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

- ν_μ disappearance experiments:

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

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

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

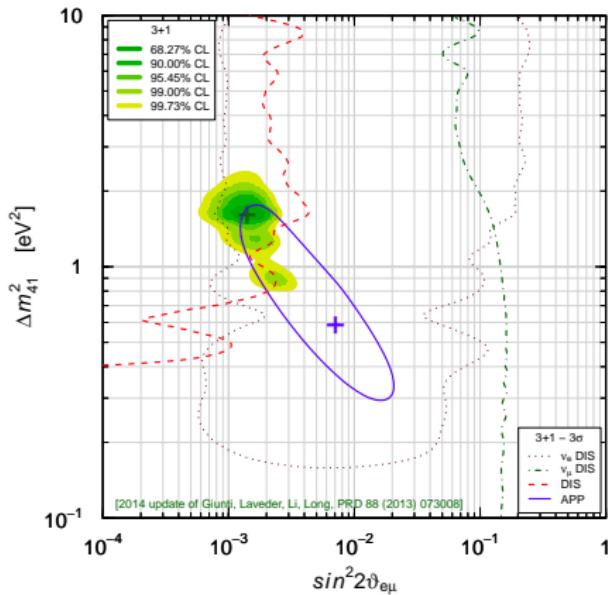
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu} \implies$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[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

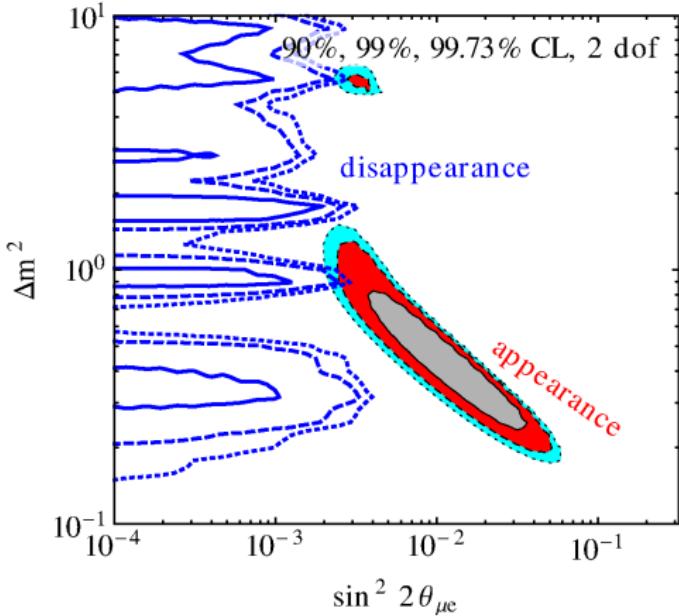
Our Fit



GoF = 5%

PGoF = 0.1%

Kopp, Machado, Maltoni, Schwetz

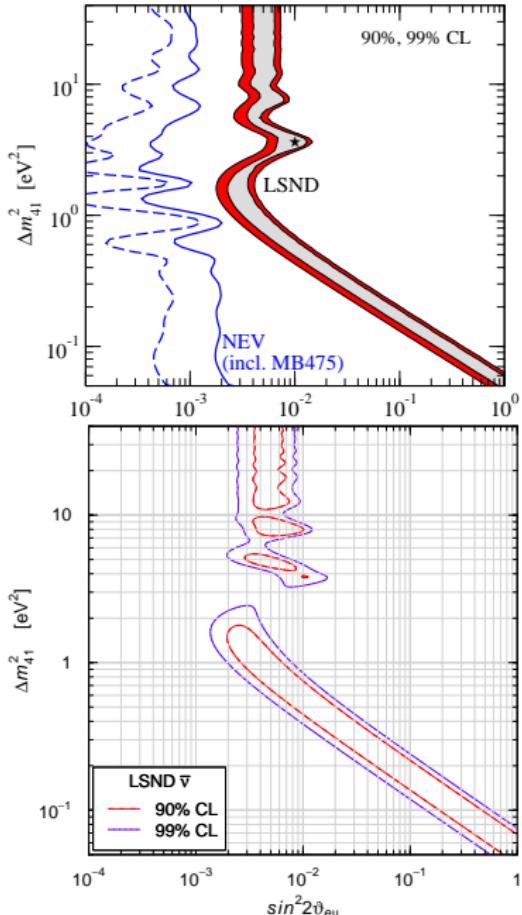


GoF = 19%

PGoF = 0.01%

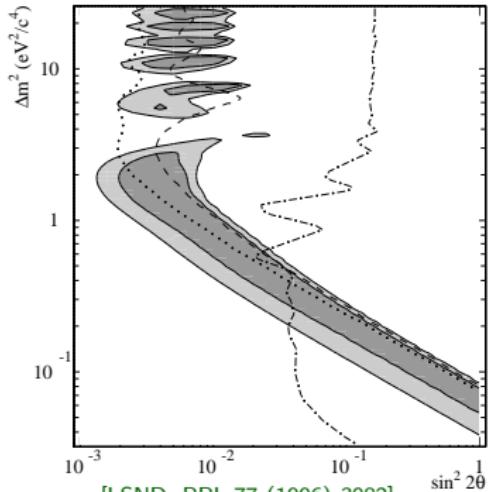
[Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

Different LSND Treatments



← Kopp, Machado, Maltoni, Schwetz

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



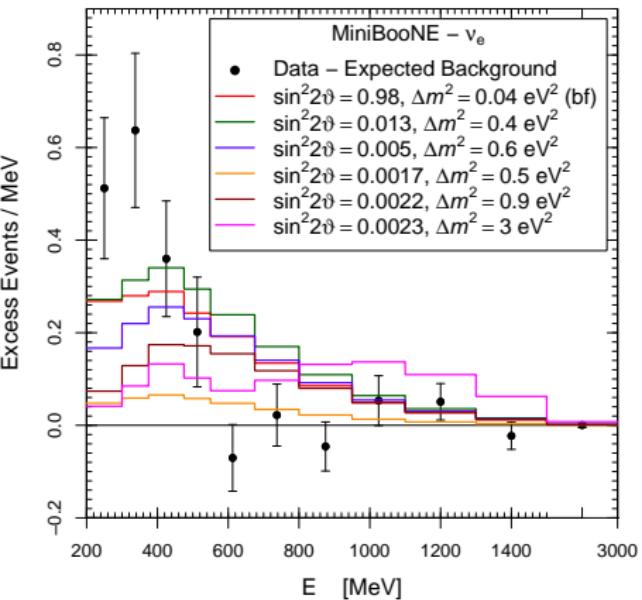
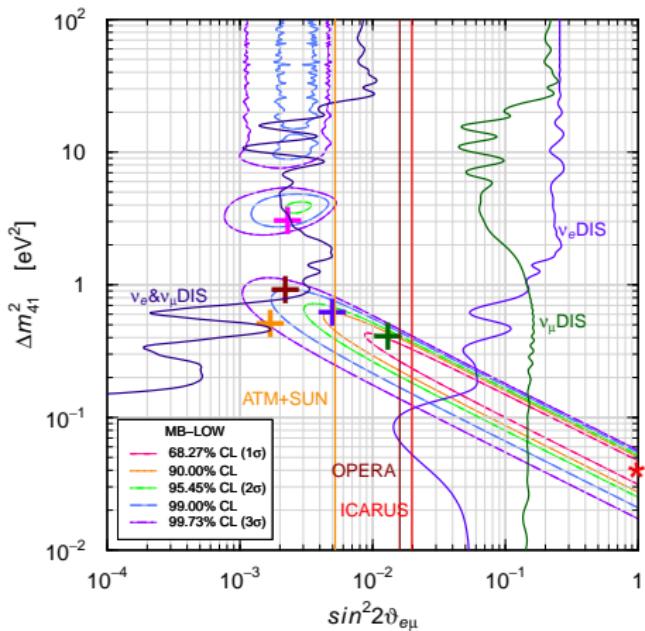
[LSND, PRL 77 (1996) 3082]

only $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ decay at rest data
 $20 < E_{e^+} < 60 \text{ MeV}$

← Our Fit

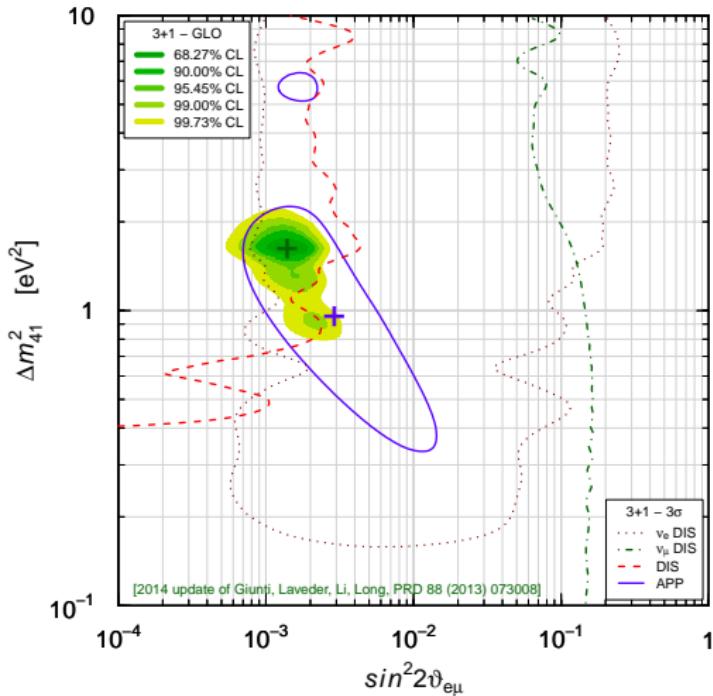
[improvement of Giunti, Laveder, PRD 82 (2010) 093016]

MiniBooNE Low-Energy Excess?



- ▶ No fit of low-energy excess for realistic $\sin^2 2\theta_{e\mu} \lesssim 5 \times 10^{-3}$
- ▶ 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



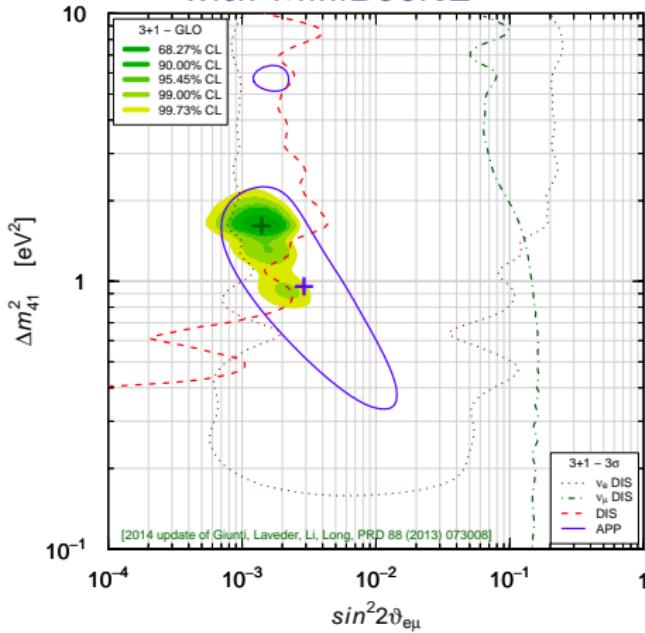
MiniBooNE $E > 475$ MeV
GoF = 26% PGOF = 7%

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

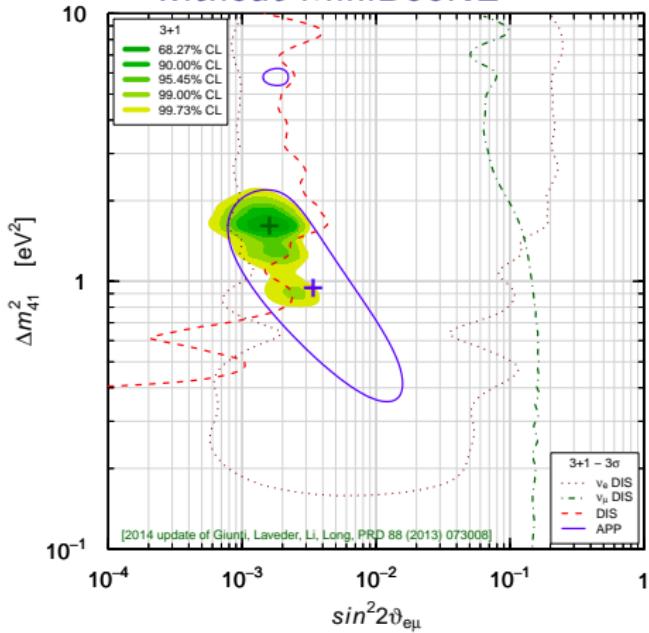
No Osc. disfavored at 6.3σ
 $\Delta\chi^2/NDF = 47.7/3$

MiniBooNE Impact in Pragmatic 3+1 Fit?

with MiniBooNE



without MiniBooNE



GoF = 26%

PGoF = 7%

No Osc. disfavored at 6.3σ

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

GoF = 16%

PGoF = 5%

No Osc. disfavored at 6.4σ

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

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

Effective SBL Oscillation Probabilities in 3+2 Schemes

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

$$\eta = \arg[U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*]$$

$$P_{\substack{(-) \\ \nu_\mu \rightarrow \nu_e}} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \phi_{51} \\ + 8|U_{\mu 4} U_{e4} U_{\mu 5} U_{e5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \eta)$$

$$P_{\substack{(-) \\ \nu_\alpha \rightarrow \nu_\alpha}} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 \phi_{41} + |U_{\alpha 5}|^2 \sin^2 \phi_{51}) \\ - 4|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 \phi_{54}$$

[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]

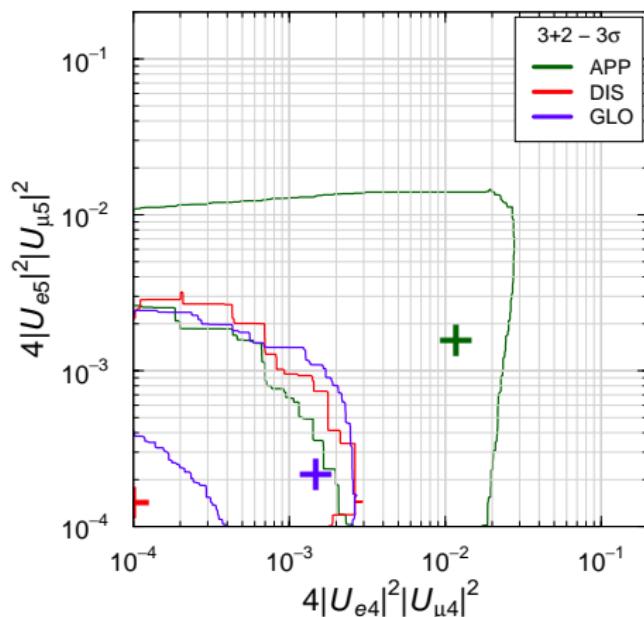
- Good: CP violation
- Bad: Two massive sterile neutrinos at the eV scale!

4 more parameters: $\underbrace{\Delta m_{41}^2, |U_{e4}|^2, |U_{\mu 4}|^2, \Delta m_{51}^2, |U_{e5}|^2, |U_{\mu 5}|^2, \eta}_{3+1}$

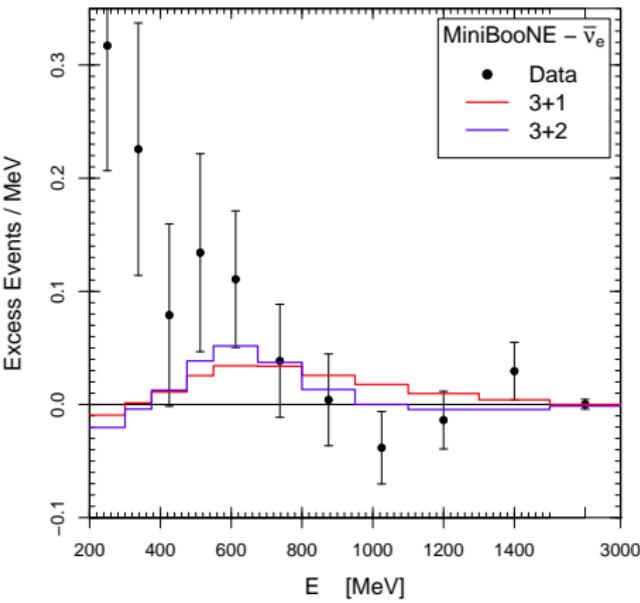
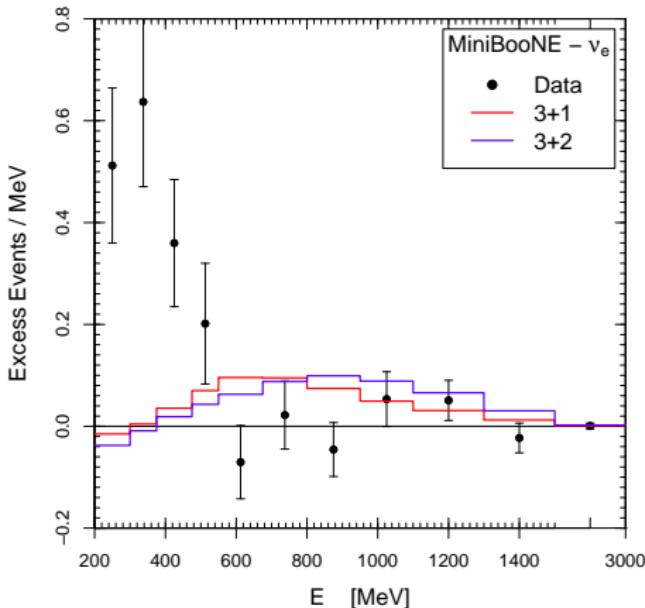
Global Fits	Our Fit		KMMS	
	3+1	3+2	3+1	3+2
GoF	5%	7%	19%	23%
PGoF	0.1%	0.04%	0.01%	0.003%

- 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

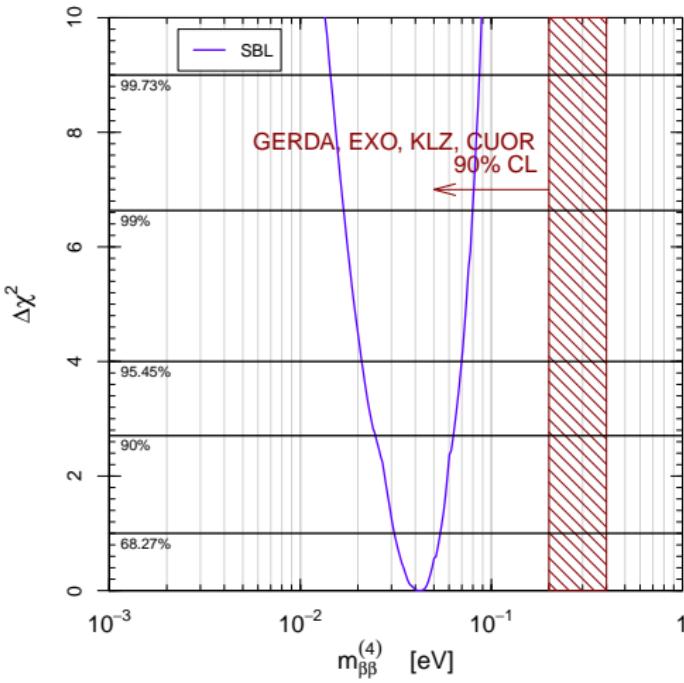


- ▶ Note difference between 3+2 ν_e and $\bar{\nu}_e$ histograms due to CP violation
- ▶ 3+2 can fit slightly better the small $\bar{\nu}_e$ excess at about 600 MeV
- ▶ 3+2 fit of low-energy excess as bad as 3+1
- ▶ Claims that 3+2 can fit low-energy excess do not take into account constraints from other 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 $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions
- ▶ final $\nu_e + 2010 \bar{\nu}_e$ MiniBooNE data indicated $\nu_e - \bar{\nu}_e$ difference
 ↓
 reasonable and useful to consider 3+2
- ▶ $\nu_e - \bar{\nu}_e$ 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 $m_{\beta\beta}^{(3\nu-IH)}$

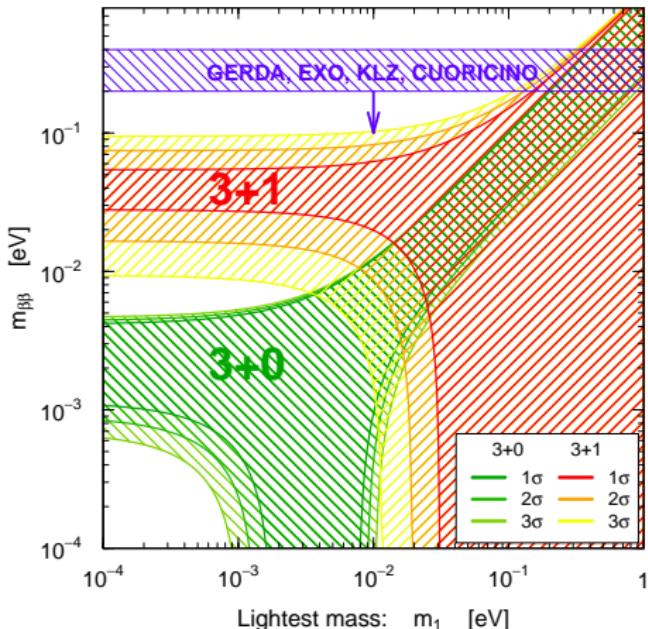
[Barry et al, JHEP 07 (2011) 091]

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

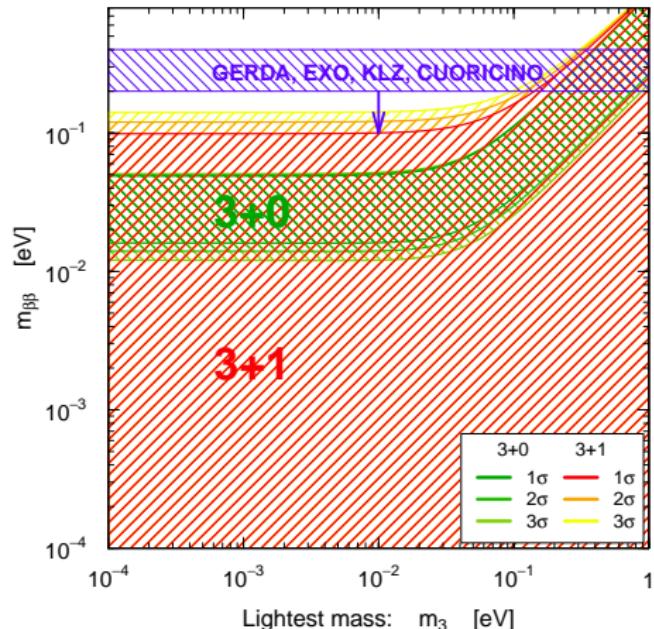
[Rodejohann, JPG 39 (2012) 124008]

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

Goodness of Fit

- ▶ Assumption or approximation: Gaussian uncertainties and linear model
- ▶ χ^2_{\min} has χ^2 distribution with Number of Degrees of Freedom

$$\text{NDF} = N_D - N_P$$

N_D = Number of Data N_P = Number of Fitted Parameters

- ▶ $\langle \chi^2_{\min} \rangle = \text{NDF}$ $\text{Var}(\chi^2_{\min}) = 2\text{NDF}$

- ▶ $\text{GoF} = \int_{\chi^2_{\min}}^{\infty} p_{\chi^2}(z, \text{NDF}) dz$ $p_{\chi^2}(z, n) = \frac{z^{n/2-1} e^{-z/2}}{2^{n/2} \Gamma(n/2)}$

Parameter Goodness of Fit

Maltoni, Schwetz, PRD 68 (2003) 033020, arXiv:hep-ph/0304176

- ▶ Measure compatibility of two (or more) sets of data points A and B under fitting model
- ▶ $\chi^2_{\text{PGoF}} = (\chi^2_{\min})_{A+B} - [(\chi^2_{\min})_A + (\chi^2_{\min})_B]$
- ▶ χ^2_{PGoF} has χ^2 distribution with Number of Degrees of Freedom

$$\text{NDF}_{\text{PGoF}} = N_P^A + N_P^B - N_P^{A+B}$$

- ▶ $\text{PGoF} = \int_{\chi^2_{\text{PGoF}}}^{\infty} p_{\chi^2}(z, \text{NDF}_{\text{PGoF}}) dz$