

Beyond Three-Neutrino Mixing: Theory and Phenomenology

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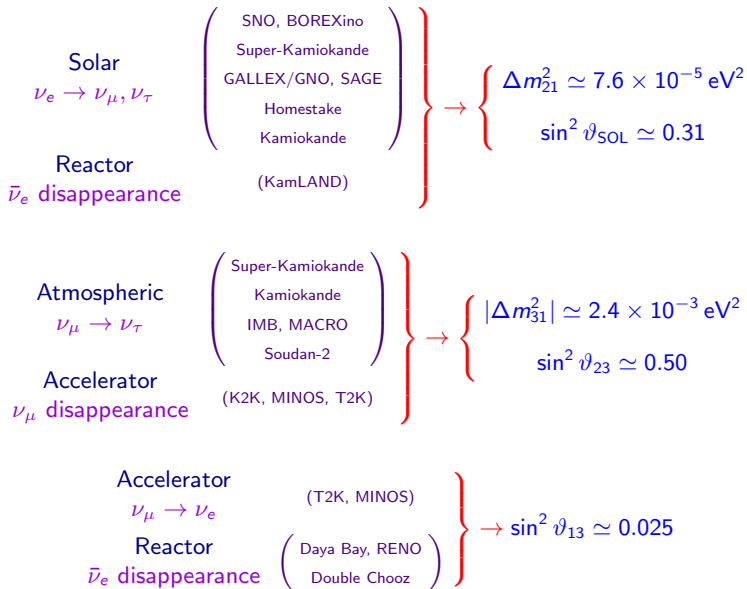
Neutrino Unbound: <http://www.nu.to.infn.it>

CIPANP 2012

11th Conference on the Intersections of Particle and Nuclear Physics

29 May - 3 June 2012, St. Petersburg, FL, USA

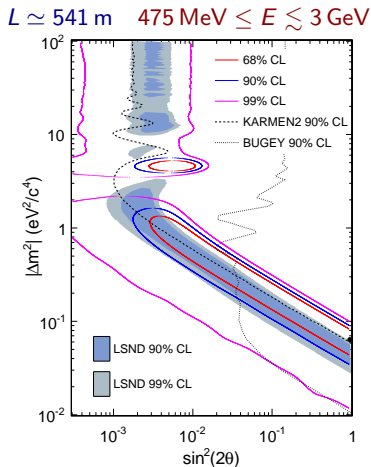
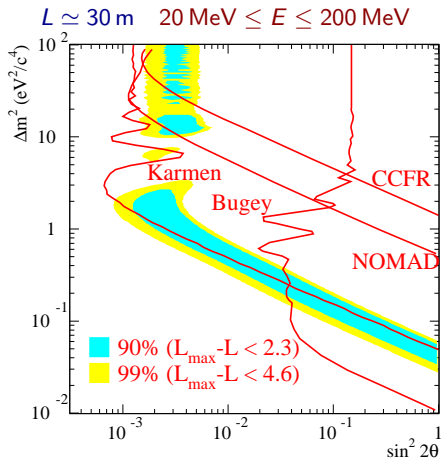
Three-Neutrino Mixing Paradigm



LSND and MiniBooNE Antineutrinos

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

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

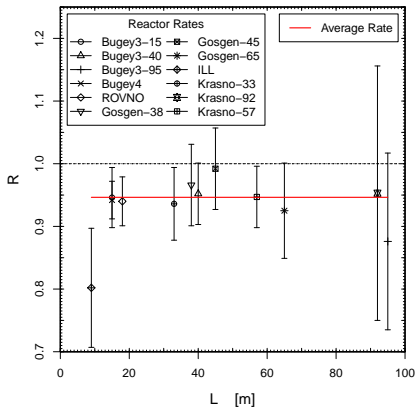


Similar L/E but different L and $E \implies$ Oscillations!

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e \quad \Delta m_{\text{SBL}}^2 \gtrsim 0.2 \text{ eV}^2 \quad (\gg \Delta m_{\text{ATM}}^2 \gg \Delta m_{\text{SOL}}^2)$$

Reactor and Gallium Anomalies

$\bar{\nu}_e$ Disappearance



$$\bar{R} = 0.946 \pm 0.024$$

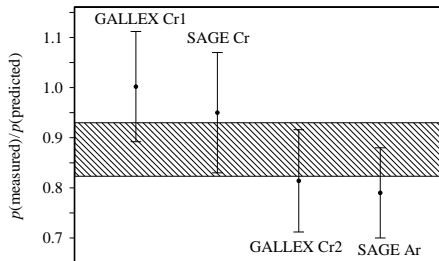
[Mention et al, PRD 83 (2011) 073006]

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

[Mueller et al, PRC 83 (2011) 054615]

[Huber, PRC 84 (2011) 024617]

ν_e Disappearance



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

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

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

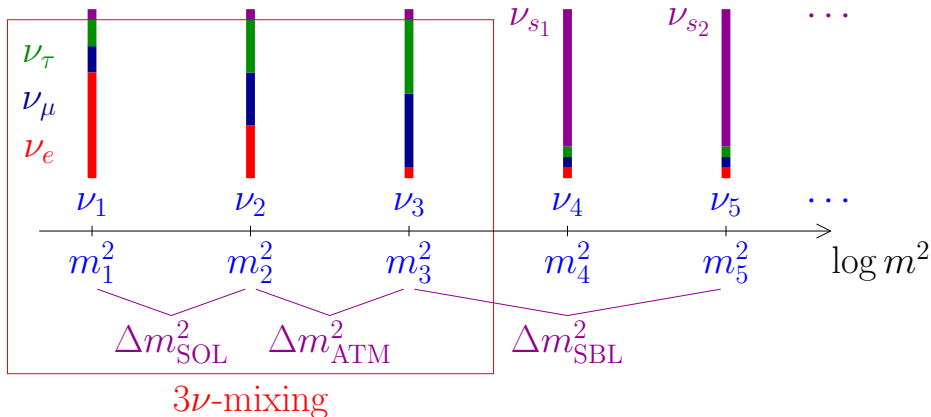
$$\bar{R} = 0.76^{+0.09}_{-0.08}$$

[Giunti, Laveder, PRC 83 (2011) 065504]

Haxton cross section with uncertainties

[Haxton, PLB 431 (1998) 110]

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 $m_D \overline{\nu_R} \nu_L$ + Majorana mass $m_M \overline{\nu_R^c} \nu_R$
- ▶ $\nu_{eL}, \nu_{\mu L}, \nu_{\tau L} + \nu_{eR}, \nu_{\mu R}, \nu_{\tau R} \implies$ 6 massive Majorana neutrinos

Sterile Neutrinos

- ▶ Light anti- ν_R are called sterile neutrinos

$$\nu_R^c \rightarrow \nu_{sL} \quad (\text{left-handed})$$

- ▶ Sterile means no standard model interactions
- ▶ Active neutrinos (ν_e, ν_μ, ν_τ) can oscillate into 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:

$$\begin{array}{ccccc} \Delta m_{21}^2 & \ll & |\Delta m_{31}^2| & \ll & |\Delta m_{41}^2| \leq \dots \\ \nu_1 & & \nu_2 & & \nu_3 & & \nu_4 & & \dots \\ \nu_e & & \nu_\mu & & \nu_\tau & & \nu_{s1} & & \dots \end{array}$$

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right) \quad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

No CP Violation!

$$P_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right) \quad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

Perturbation of 3ν Mixing

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

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

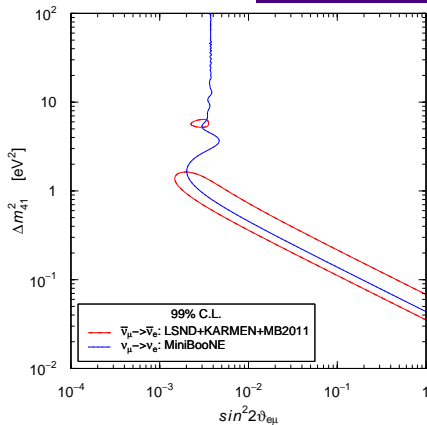
↑
SBL

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



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

CP Violation?



3+1

GoF = 36%

PGoF = 3.3%

▶ 3+1 \implies Tension between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ data.

▶ 3+2 \implies CP Violation [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]

▶ 3+1+NSI \implies CP Violation [Akhmedov, Schwetz, JHEP 10 (2010) 115]

Effective SBL Oscillation Probabilities in 3+2 Schemes

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

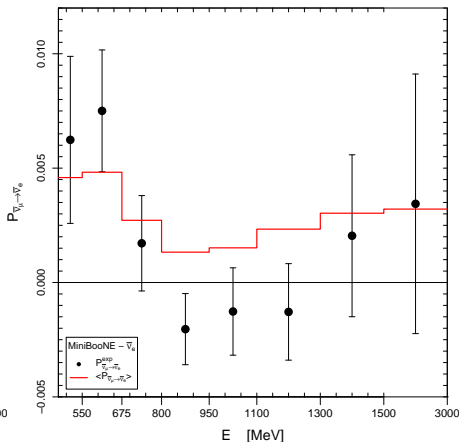
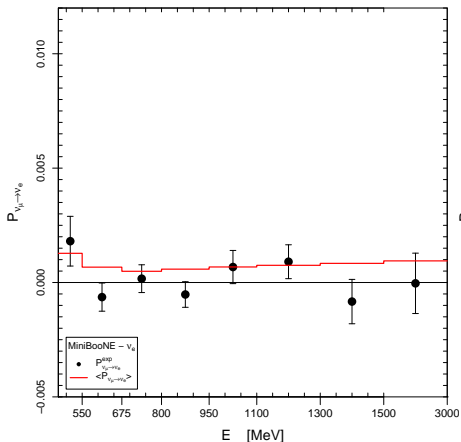
$$\eta = \arg[U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*]$$

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

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

- ▶ **Good:** CP violation can solve the $\nu_{\mu} \rightarrow \nu_e$ vs $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$ tension.
- ▶ **Bad:**
 - ▶ More parameters: 7 (vs 3 in 3+1)
 - ▶ 2 sterile neutrinos are disfavored by BBN.
 - ▶ A large sum of masses is disfavored by CMB+LSS.

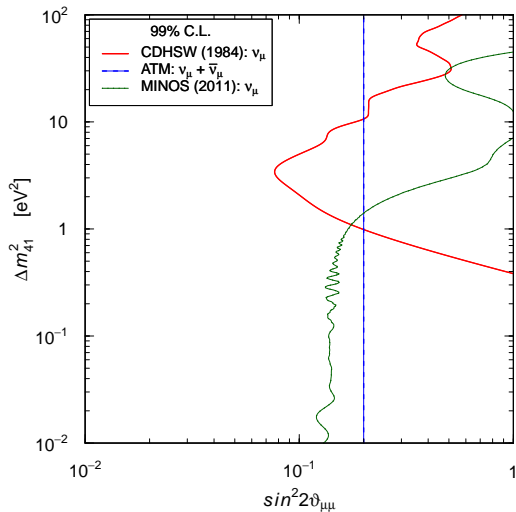
3+2: MiniBooNE $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



$$\begin{aligned}
 P_{(-)}^{(-)} = & 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2|U_{\mu5}|^2 \sin^2 \phi_{51} \\
 & + 4|U_{e4}U_{\mu4}U_{e5}U_{\mu5}| \cos \eta [\sin^2 \phi_{41} + \sin^2 \phi_{51} - \sin^2 \phi_{54}] \\
 & - 2|U_{e4}U_{\mu4}U_{e5}U_{\mu5}| \sin \eta [\sin(2\phi_{41}) - \sin(2\phi_{51}) + \sin(2\phi_{54})]
 \end{aligned}$$

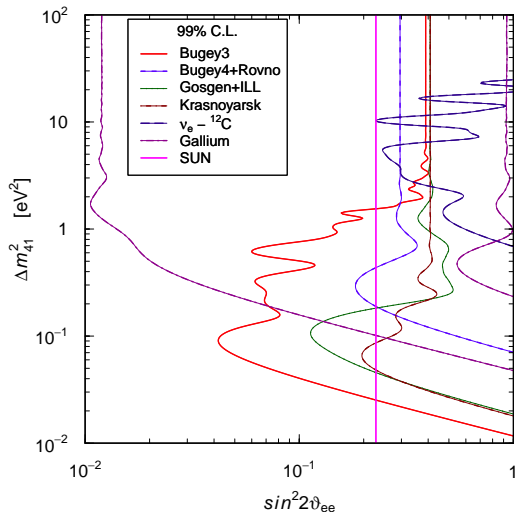
Disappearance Constraints

ν_μ and $\bar{\nu}_\mu$ Disappearance



- ▶ ATM constraint on $|U_{\mu 4}|^2$
[Maltoni, Schwetz, PRD 76 (2007) 093005]
- ▶ MINOS constraint on $|U_{\mu 4}|^2$
[Giunti, Laveder, PRD 84 (2011) 093006]

ν_e and $\bar{\nu}_e$ Disappearance



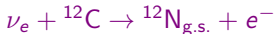
▶ New Reactor $\bar{\nu}_e$ Fluxes

[Mueller et al., PRC 83 (2011) 054615]

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

[Huber, PRC 84 (2011) 024617]

▶ KARMEN + LSND



[Conrad, Shaevitz, PRD 85 (2012) 013017]

[Giunti, Laveder, PLB 706 (2011) 200]

▶ SUN&KamLAND + ϑ_{13}

[Giunti, Li, PRD 80 (2009) 113007]

[Palazzo, PRD 83 (2011) 113013]

[Palazzo, PRD 85 (2012) 077301]

SUN&KamLAND + ϑ_{13} bound on $|U_{e4}|^2$

[Giunti, Li, PRD 80 (2009) 113007; Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301]

3+1 with simplifying assumptions: $U_{\mu 4} = U_{\tau 4} = 0$, no CP violation

$$U_{e1} = c_{12}c_{13}c_{14} \quad U_{e2} = s_{12}c_{13}c_{14} \quad U_{e3} = s_{13}c_{14} \quad U_{e4} = s_{14}$$

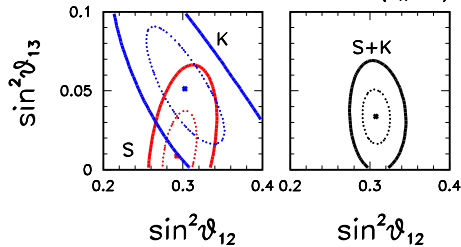
$$U_{s1} = -c_{12}c_{13}s_{14} \quad U_{s2} = -s_{12}c_{13}s_{14} \quad U_{s3} = -s_{13}s_{14} \quad U_{s4} = c_{14}$$

$$P_{\nu_e \rightarrow \nu_e} = c_{13}^4 c_{14}^4 P_{\nu_e \rightarrow \nu_e}^{2\nu} + s_{13}^4 c_{14}^4 + s_{14}^4$$

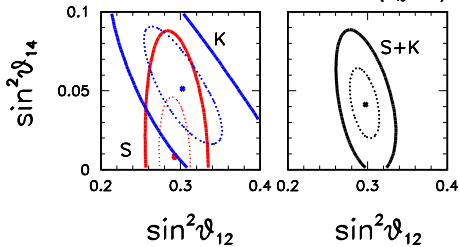
$$P_{\nu_e \rightarrow \nu_s} = c_{14}^2 s_{14}^2 (c_{13}^4 P_{\nu_e \rightarrow \nu_s}^{2\nu} + s_{13}^4 + 1)$$

$$\begin{aligned} V &= c_{13}^2 c_{14}^2 V_{CC} - c_{13}^2 s_{14}^2 V_{NC} \\ &= (|U_{e1}|^2 + |U_{e2}|^2) V_{CC} - (|U_{s1}|^2 + |U_{s2}|^2) V_{NC} \end{aligned}$$

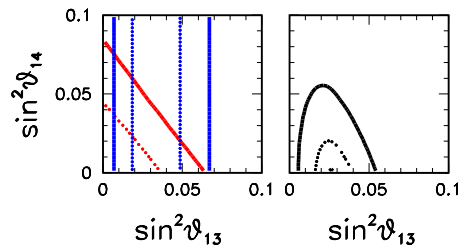
Solar and KamLAND constraints ($\vartheta_{14} = 0$)



Solar and KamLAND constraints ($\vartheta_{13} = 0$)



[Palazzo, PRD 83 (2011) 113013]



$$\sin^2 \vartheta_{13} = 0.025 \pm 0.004$$

$$|U_{e4}|^2 = \sin^2 \vartheta_{14} \lesssim 0.02 (1\sigma)$$

[Palazzo, PRD 85 (2012) 077301]

3+1

- ▶ 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:

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

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

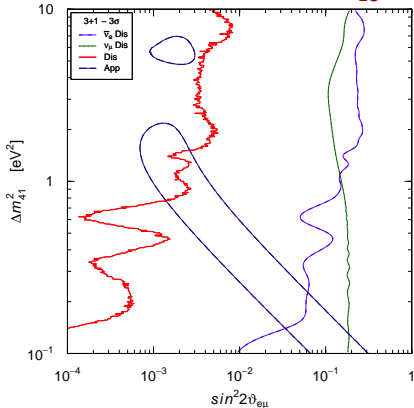
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2 |U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

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

[Okada, Yasuda, Int. J. Mod. Phys. A12 (1997) 3669-3694]

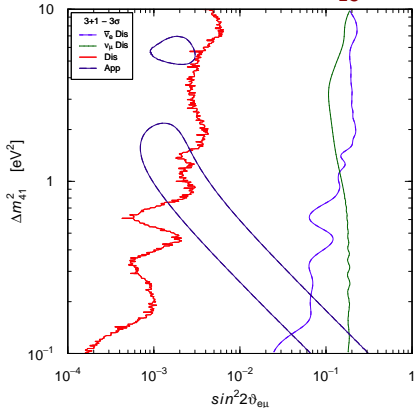
[Bilenky, Giunti, Grimus, Eur. Phys. J. C1 (1998) 247]

3+1 without SUN&KL+ ϑ_{13}



GoF = 45% PGoF = 0.4%

3+1 with SUN&KL+ ϑ_{13}



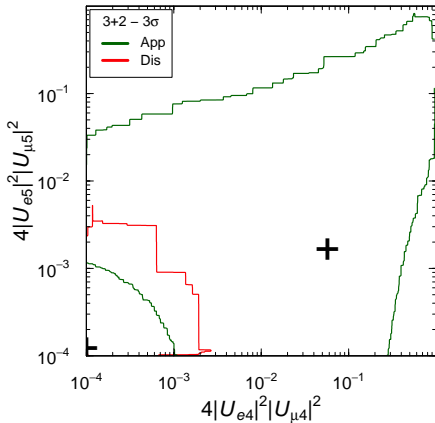
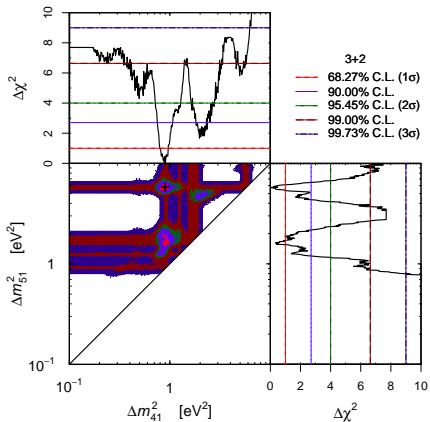
GoF = 38% PGoF = 0.3%

▶ 3+1 & 3+2: Appearance-Disappearance tension

▶ Tension reduced in 3+1+NSI [Akhmedov, Schwetz, JHEP 10 (2010) 115]

▶ No tension in 3+1+CPTV [Barger, Marfatia, Whisnant, PLB 576 (2003) 303]
 [Giunti, Laveder, PRD 82 (2010) 093016, PRD 83 (2011) 053006]

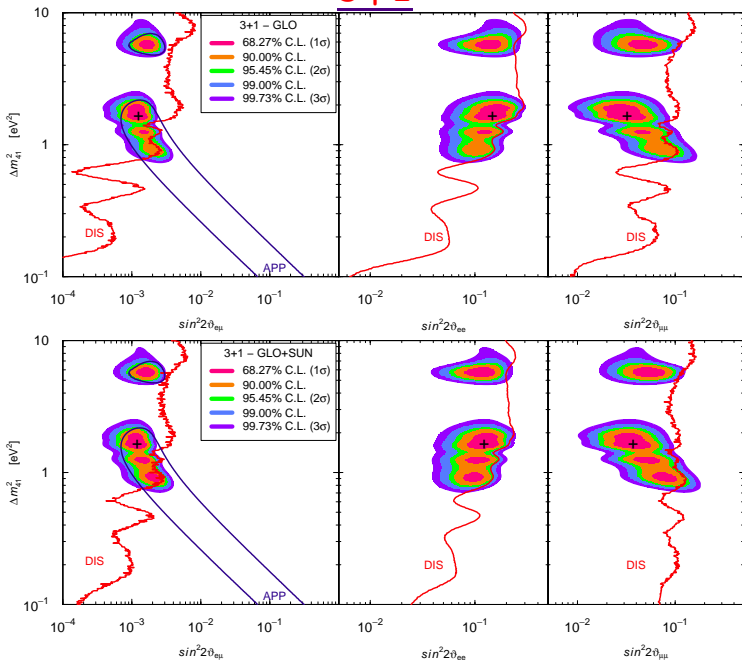
3+2 with SUN&KamLAND+ ν_{13}



GoF = 46% PGoF = 0.29%

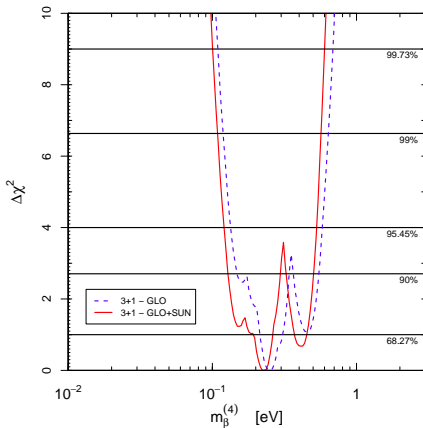
3+2 is preferred to 3+1 only for
 CP-violating MiniBooNE neutrino antineutrino difference

3+1



Testable Implications

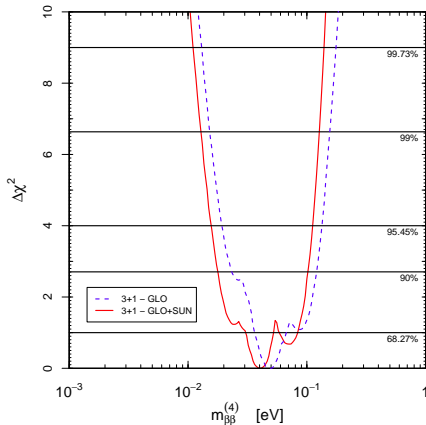
β Decay



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

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

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



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

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

Cosmology

- ▶ N_s = number of thermalized sterile neutrinos (not necessarily integer)
- ▶ CMB and LSS in Λ CDM: $N_s = 1.3 \pm 0.9$ $m_s < 0.66$ eV (95% C.L.)

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

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

[Giusarma, Corsi, Archidiacono, de Putter, Melchiorri, Mena, Pandolfi, PRD 83 (2011) 115023]

$$N_s = 1.12^{+0.86}_{-0.74} \quad (95\% \text{ C.L.}) \quad [\text{Archidiacono, Calabrese, Melchiorri, PRD 84 (2011) 123008}]$$

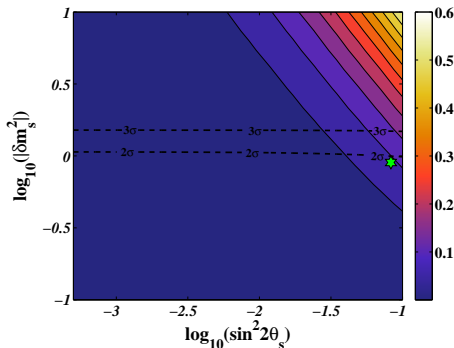
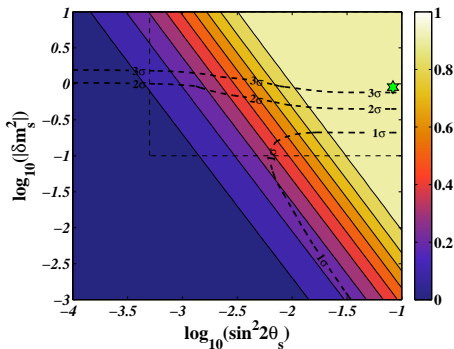
- ▶ BBN:
$$\begin{cases} N_s = 0.22 \pm 0.59 & [\text{Cyburt, Fields, Olive, Skillman, AP 23 (2005) 313}] \\ N_s = 0.64^{+0.40}_{-0.35} & [\text{Izotov, Thuan, ApJL 710 (2010) L67}] \\ N_s \leq 1 \text{ at } 95\% \text{ C.L.} & [\text{Mangano, Serpico, PLB 701 (2011) 296}] \end{cases}$$

- ▶ CMB+LSS+BBN: $N_s = 0.85^{+0.39}_{-0.56}$ (95% C.L.)

[Hamann, Hannestad, Raffelt, Wong, JCAP 1109 (2011) 034]

Thermalisation of Sterile Neutrinos

[Hannestad, Tamborra, Tram, arXiv:1204.5861]



lepton asymmetry = 0

lepton asymmetry = 10^{-2}

Color: thermalized iso- N_s contours

Star: 3+1 best fit [Giunti, Laveder, PLB 706 (2011) 200]

Dashed lines: CMB+LSS constraints [Hamann et al, PRL 105 (2010) 181301]

Conclusions

- ▶ Suggestive LSND, MiniBooNE, Reactor and Gallium indications in favor of short-baseline neutrino oscillations \implies sterile neutrinos
- ▶ Recent measurement of $|U_{e3}|^2$ and SUN+KamLAND data restrict range of $|U_{e4}|^2$ allowed by reactor short-baseline data for $\Delta m_{\text{SBL}}^2 \gtrsim 1 \text{ eV}^2$.
- ▶ 3+1 Neutrino Mixing:
 - ▶ No CP violation \implies Neutrinos vs Antineutrinos tension
 - ▶ Appearance vs Disappearance tension
 - ▶ Tension with standard cosmology (or large lepton asymmetry)
- ▶ 3+2 Neutrino Mixing:
 - ▶ CP violation \implies no Neutrinos vs Antineutrinos tension
 - ▶ Appearance vs Disappearance tension
 - ▶ More tension with standard cosmology (or large lepton asymmetry)
- ▶ Simpler 3+1 Neutrino Mixing may be enough (Occam's Razor).
- ▶ New short-baseline neutrino oscillation experiments are needed!