Phenomenology of Light Sterile Neutrinos

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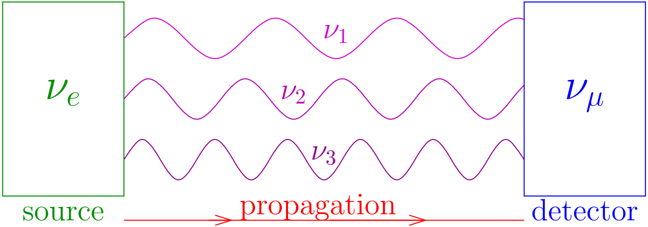
Neutrino Oscillations

- Neutrino Oscillations are Flavor Transitions which oscillate with distance.
- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector
- A Flavor Neutrino is a superposition of Massive Neutrinos

$$
\begin{aligned}
|\nu_e\rangle &= U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle \\
|\nu_\mu\rangle &= U_{\mu1}\,|\nu_1\rangle + U_{\mu2}\,|\nu_2\rangle + U_{\mu3}\,|\nu_3\rangle \\
|\nu_\tau\rangle &= U_{\tau1}\,|\nu_1\rangle + U_{\tau2}\,|\nu_2\rangle + U_{\tau3}\,|\nu_3\rangle
\end{aligned}
$$

- U is the 3×3 Neutrino Mixing Matrix

$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle$$



$$|\nu(t>0)\rangle = U_{e1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{e2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{e3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_e\rangle$$

$$E_k^2 = p^2 + m_k^2$$

at the detector there is a probability > 0 to see the neutrino as a ν_μ

Neutrino Oscillations are Flavor Transitions $\propto \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right)$

$$\begin{array}{cccc} \nu_e \to \nu_\mu & \nu_e \to \nu_\tau & \nu_\mu \to \nu_e & \nu_\mu \to \nu_\tau \\ \bar{\nu}_e \to \bar{\nu}_\mu & \bar{\nu}_e \to \bar{\nu}_\tau & \bar{\nu}_\mu \to \bar{\nu}_e & \bar{\nu}_\mu \to \bar{\nu}_\tau \end{array}$$

transition probabilities depend on U and $\Delta m^2_{kj} \equiv m_k^2 - m_j^2$

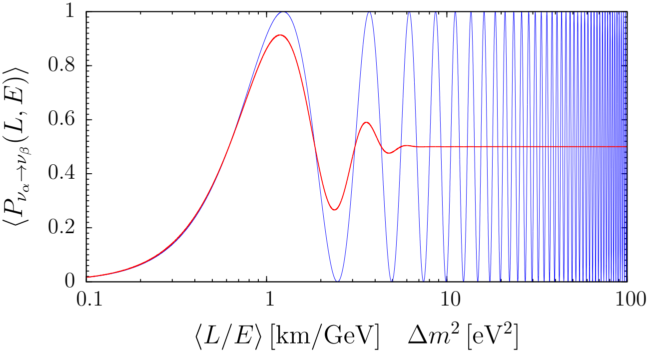
Two-Neutrino Mixing and Oscillations

$$|\nu_\alpha\rangle = \cos\vartheta\,|\nu_1\rangle + \sin\vartheta\,|\nu_2\rangle$$
$$|\nu_\beta\rangle = -\sin\vartheta\,|\nu_1\rangle + \cos\vartheta\,|\nu_2\rangle$$

$$\Delta m^2 \equiv \Delta m^2_{21} \equiv m^2_2 - m^2_1$$

Transition Probability: $$P_{\nu_\alpha\to\nu_\beta} = P_{\nu_\beta\to\nu_\alpha} = \sin^2 2\vartheta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

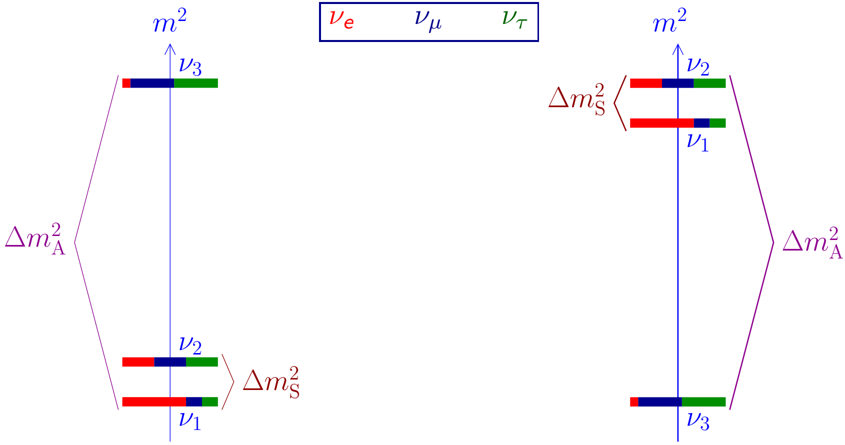
Survival Probabilities: $$P_{\nu_\alpha\to\nu_\alpha} = P_{\nu_\beta\to\nu_\beta} = 1 - P_{\nu_\alpha\to\nu_\beta}$$



Experimental Evidences of Neutrino Oscillations

Source	Experiments	Result
Solar $\nu_e \to \nu_\mu, \nu_\tau$	SNO, BOREXino, Super-Kamiokande, GALLEX/GNO, SAGE, Homestake, Kamiokande	$\to$ $\Delta m^2_{\text{S}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$, $\sin^2\vartheta_{\text{S}} \simeq 0.30$
VLBL Reactor $\bar{\nu}_e$ disappearance	(KamLAND)	
Atmospheric $\nu_\mu \to \nu_\tau$	Super-Kamiokande, Kamiokande, IMB, MACRO, Soudan-2	$\to$ $\Delta m^2_{\text{A}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2$, $\sin^2\vartheta_{\text{A}} \simeq 0.50$
LBL Accelerator ν_μ disappearance	(K2K, MINOS, T2K)	
LBL Accelerator $\nu_\mu \to \nu_\tau$	(Opera)	
LBL Accelerator $\nu_\mu \to \nu_e$	(T2K, MINOS)	$\to$ Δm^2_{A}, $\sin^2\vartheta_{13} \simeq 0.023$
LBL Reactor $\bar{\nu}_e$ disappearance	Daya Bay, RENO, Double Chooz	

Three-Neutrino Mixing Paradigm



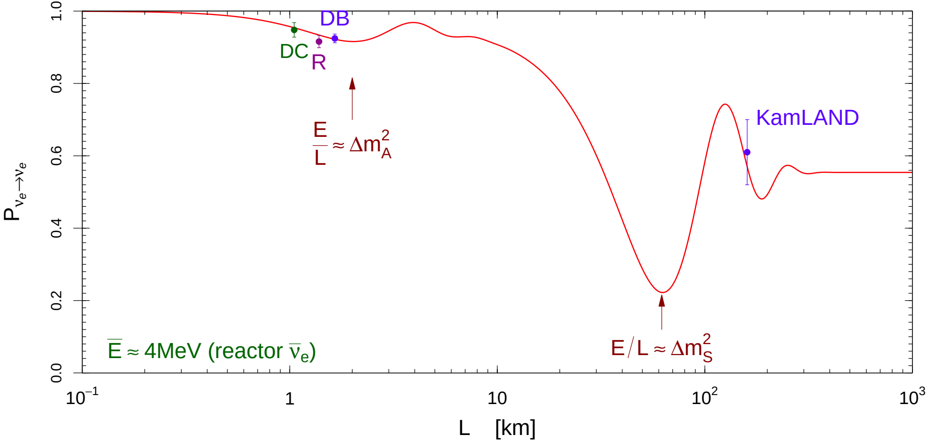
Normal Ordering

$\Delta m^2_{31} > \Delta m^2_{32} > 0$

Inverted Ordering

$\Delta m^2_{32} < \Delta m^2_{31} < 0$

absolute scale is not determined by neutrino oscillation data


DB
DC
R
KamLAND
$\frac{E}{L} \approx \Delta m^2_A$
$E/L \approx \Delta m^2_S$
$\overline{E} \approx$ 4MeV (reactor $\overline{\nu}_e$)
$P_{\nu_e \to \nu_e}$
0.0
0.2
0.4
0.6
0.8
1.0
10^{-1}
1
10
10^2
10^3
L [km]

$$\Delta m^2_{\text{S}} = \Delta m^2_{21} \simeq 7.5^{+0.3}_{-0.2} \times 10^{-5}\,\text{eV}^2 \qquad \text{uncertainty} \simeq 3\%$$

$$\Delta m^2_{\text{A}} = |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq 2.4^{+0.1}_{-0.1} \times 10^{-3}\,\text{eV}^2 \qquad \text{uncertainty} \simeq 4\%$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

$\vartheta_{23} = \vartheta_{\text{A}}$

$\sin^2\vartheta_{23} \simeq 0.4 - 0.6$

$P_{\text{osc}} \propto \sin^2 2\vartheta_{23}$

maximal and flat

at $\vartheta_{23} = 45^\circ$

Daya Bay, RENO

Double Chooz

T2K, MINOS

$\sin^2\vartheta_{13} \simeq 0.023 \pm 0.002$

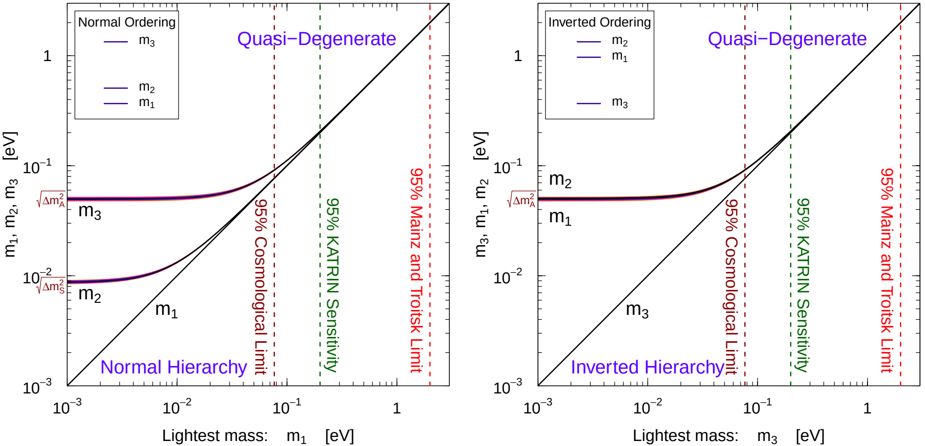
$\vartheta_{12} = \vartheta_{\text{S}}$

$\sin^2\vartheta_{12} \simeq 0.30 \pm 0.01$

$\beta\beta_{0\nu}$

$$\frac{\delta\sin^2\vartheta_{23}}{\sin^2\vartheta_{23}} \simeq 40\% \qquad \frac{\delta\sin^2\vartheta_{13}}{\sin^2\vartheta_{13}} \simeq 10\% \qquad \frac{\delta\sin^2\vartheta_{12}}{\sin^2\vartheta_{12}} \simeq 5\%$$

Absolute Scale of Neutrino Masses



$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_S^2$$
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$

$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_A^2$$
$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

Quasi-Degenerate for $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gtrsim \sqrt{\Delta m_A^2} \simeq 5 \times 10^{-2}\,\mathrm{eV}$

95% Cosmological Limit: Planck + WMAP9 + highL + BAO [arXiv:1303.5076]

Open Problems

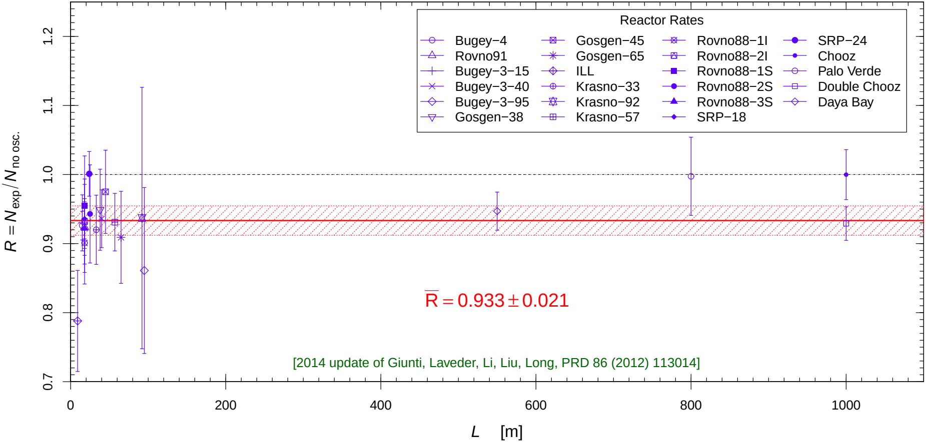
- $\vartheta_{23} \lesseqgtr 45^\circ$?
  - T2K (Japan), NOνA (USA), PINGU (Antarctica), ORCA (EU), INO (India), ...
- Mass Ordering (Hierarchy) ?
  - NOνA (USA), JUNO (China), RENO-50 (Korea), PINGU (Antarctica), ORCA (EU), INO (India), ...
- CP violation ?
  - NOνA (USA), LBNF (USA), HyperK (Japan), ...
- Absolute Mass Scale ?
  - β Decay, Neutrinoless Double-β Decay, Cosmology, ...
- Dirac or Majorana ?
  - Neutrinoless Double-β Decay, ...
- Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

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]



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

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

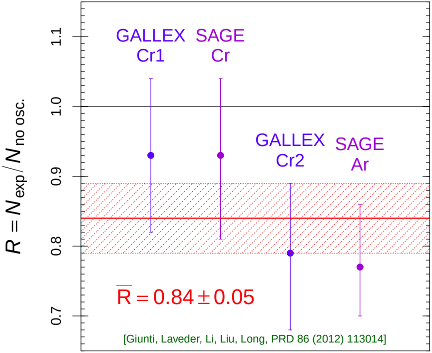
[see also: Sinev, arXiv:1103.2452; Ciuffoli, Evslin, Li, JHEP 12 (2012) 110; Zhang, Qian, Vogel, PRD 87 (2013) 073018; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050; Ivanov et al, PRC 88 (2013) 055501]

Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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



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

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

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

$\sim 2.9\sigma$ 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]

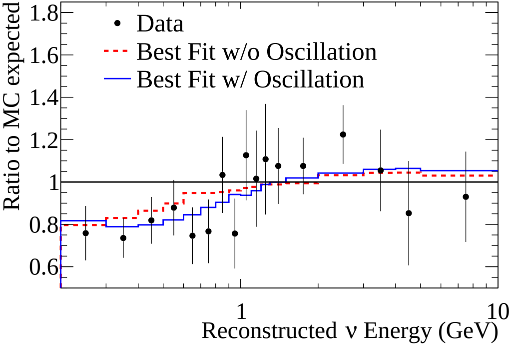
[Mention et al, PRD 83 (2011) 073006]

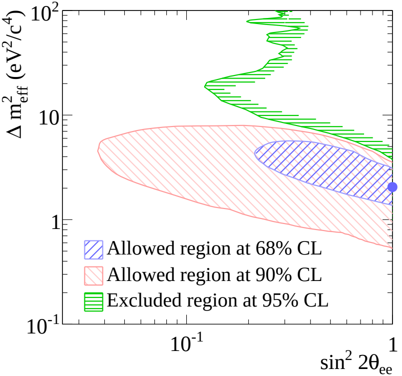
- ${}^{3}\text{He} + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + {}^{3}\text{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]
- $E_{\text{th}}(\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-) = 233.5 \pm 1.2\,\text{keV}$ [Frekers et al., PLB 722 (2013) 233]

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: $\chi^2_{\text{min}}/\text{NDF} = 45.86/51$

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

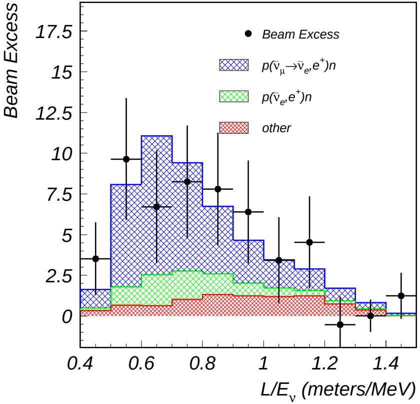
$\Delta\chi^2/\text{NDF} = 3.7/2$

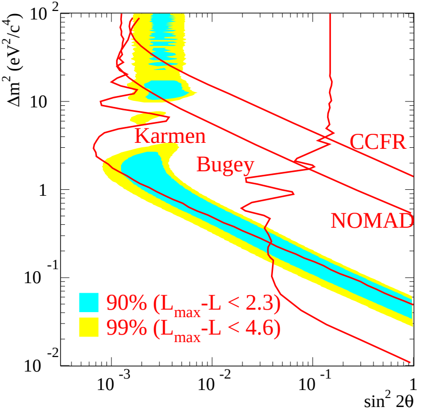
$\sim 1.4\sigma$ deviation

LSND

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

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



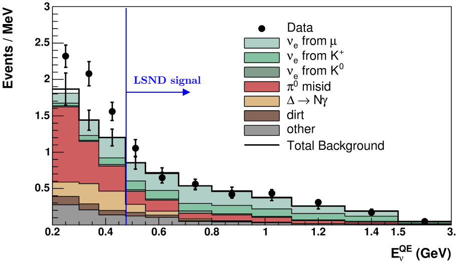


3.8σ excess $\quad \Delta m^2 \gtrsim 0.2\,\mathrm{eV}^2 \quad (\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

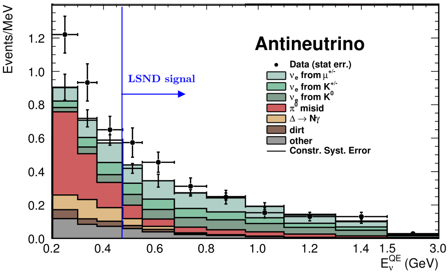
MiniBooNE

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

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



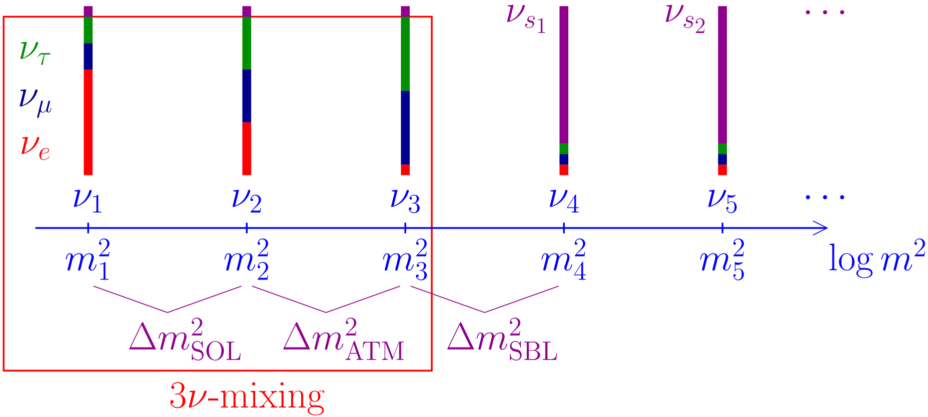
$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



- 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
- $\mathcal{L}^{\text{D}} \sim \overline{L_L}\widetilde{\Phi}\nu_R \xrightarrow[\text{Breaking}]{\text{Symmetry}} \frac{v}{\sqrt{2}} \overline{\nu_L}\nu_R$ $\quad$ 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 $\sim \overline{\nu_R^c}\nu_R$
- Diagonalization of mass matrix $\sim \begin{pmatrix} 0 & m_{\text{D}} \\ m_{\text{D}} & m_{\text{R}} \end{pmatrix} \Longrightarrow$ 2 massive Majorana neutrinos
- If mass splitting is small we have active-sterile $\nu_L \to \nu_R^c$ oscillations

- 3 left-handed + N_s right-handed fields $\Longrightarrow$ $(3+N_s)\times(3+N_s)$ mass matrix
- Diagonalization $\Longrightarrow$ $3+N_s$ massive Majorana neutrinos
- Light anti-ν_R are light sterile neutrinos

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

- 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 $\sim 1\,\text{eV}$ 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]
    [Boyarsky, Iakubovskyi, Ruchayskiy, Phys. Dark Univ. 1 (2012) 136]
    [Drewes, IJMPE, 22 (2013) 1330019]

Effective SBL Oscillation Probabilities in 3+1 Schemes

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

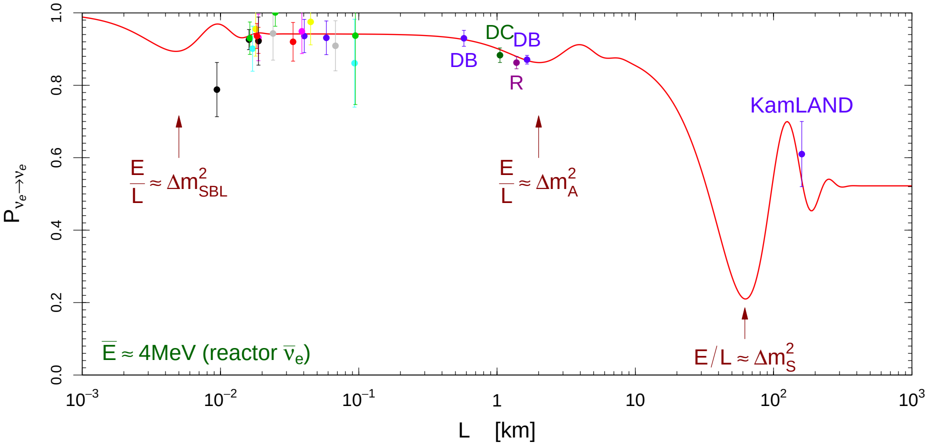
$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

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 current SBL experiments!
- May be observable in future high-precision solar exp. sensitive to Δm^2_{21} [Long, Li, Giunti, PRD 87, 113004 (2013) 113004] and accelerator exp. sensitive to Δm^2_{31} [de Gouvea, Kelly, Kobach, arXiv:1412.1479]



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

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:

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

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

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

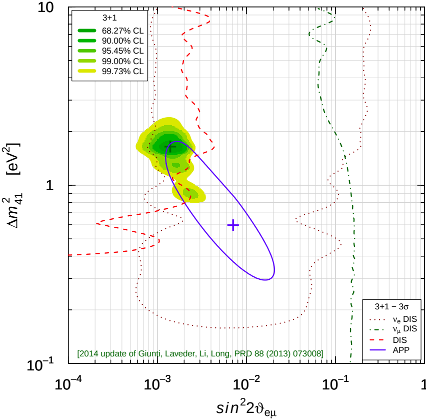
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu} \Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[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

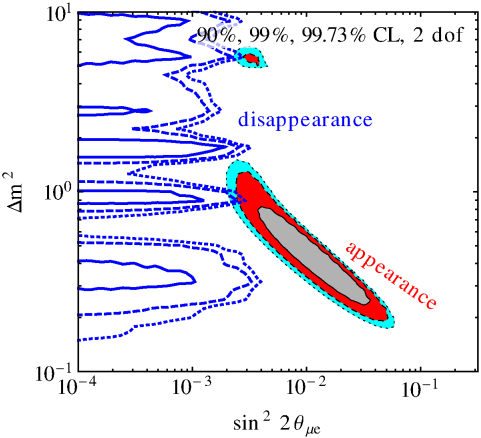
Our Fit



GoF = 5%

PGoF = 0.1%

Kopp, Machado, Maltoni, Schwetz



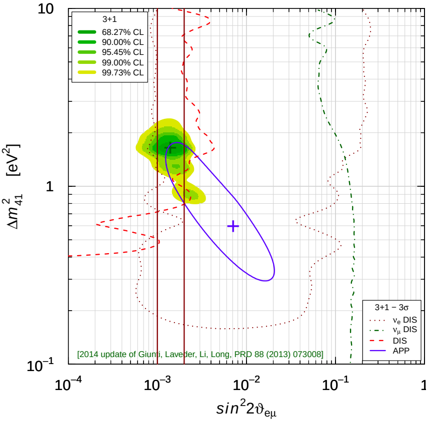
GoF = 19%

PGoF = 0.01%

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

Global 3+1 Fit

Our Fit



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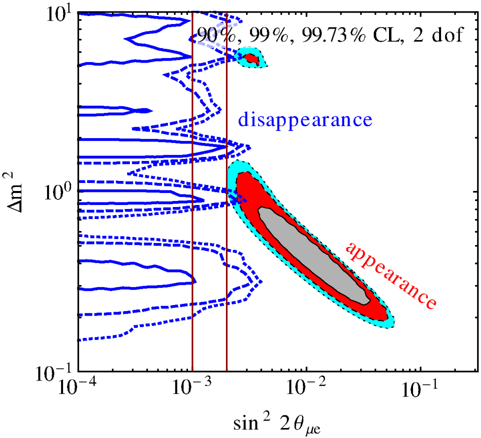


GoF = 19%

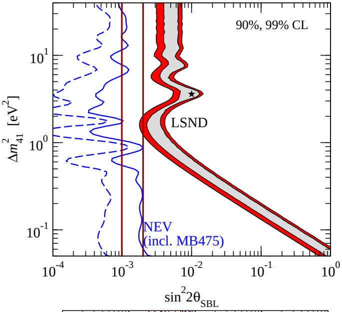
PGoF = 0.01%

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

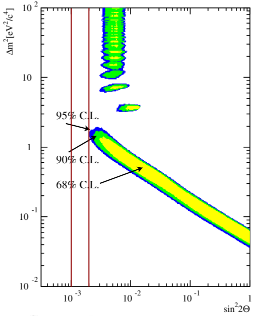
Different LSND Treatments

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

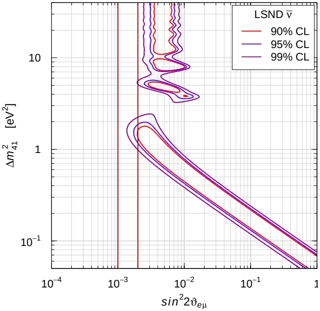
[Kopp, Machado, Maltoni, Schwetz]
[Maltoni, Schwetz, PRD 76 (2007) 093005]



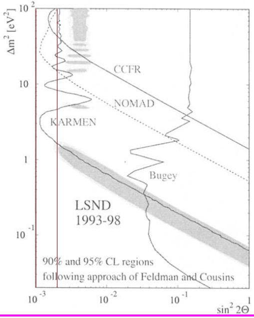
[Church, Eitel, Mills, Steidl, PRD 66 (2002) 013001]



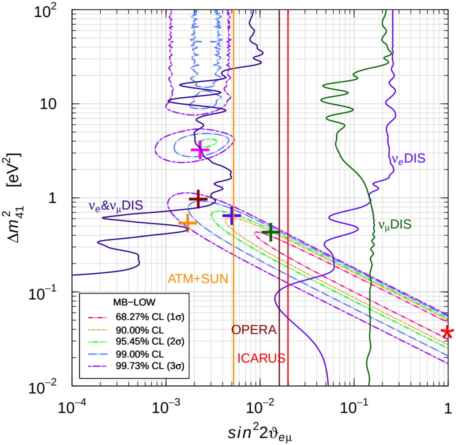
[Our Fit]
[improvement of Giunti, Laveder, PRD 82 (2010) 093016]

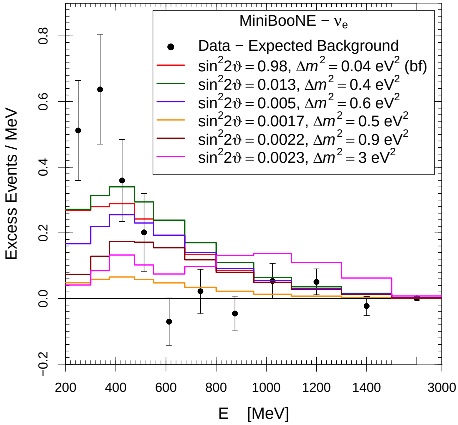


[Church (LSND), NPA 663 (2000) 799]



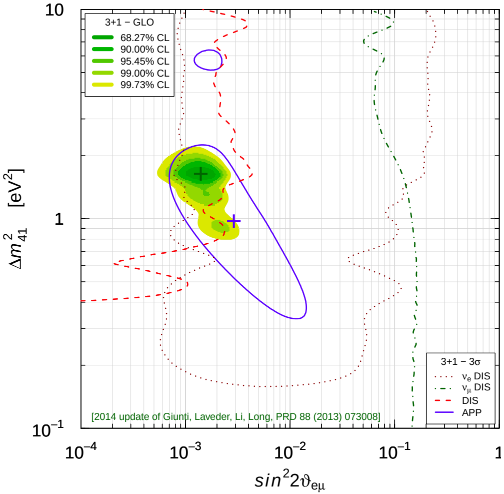
MiniBooNE Low-Energy Excess?





- 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 $= 7\%$

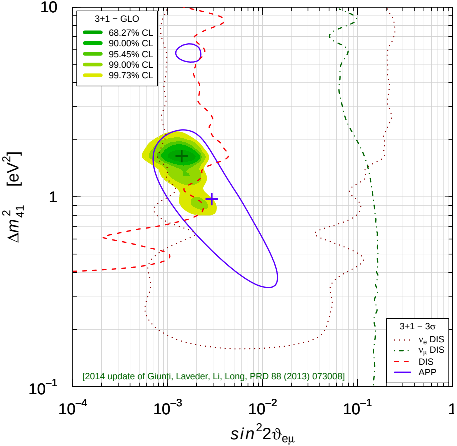
- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND ($\nu_s$), MiniBooNE (?), OPERA (~~ν_s~~), ICARUS (~~ν_s~~), KARMEN (~~ν_s~~), NOMAD (~~ν_s~~), BNL-E776 (~~ν_s~~)
- DIS ν_e & $\bar{\nu}_e$: Reactors (ν_s), Gallium (ν_s), ν_eC (~~ν_s~~), Solar (~~ν_s~~)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW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

No Osc. disfavored at 6.3σ

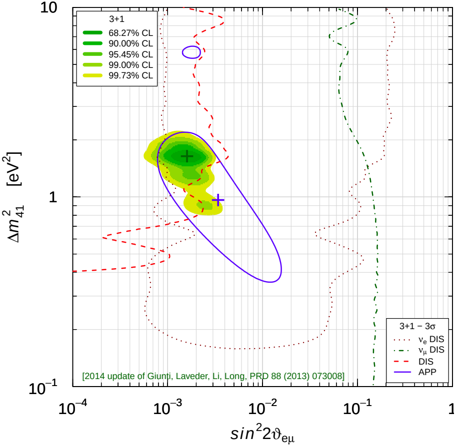
$\Delta\chi^2/\text{NDF} = 47.7/3$

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
$\Delta\chi^2/\text{NDF} = 47.7/3$	$\Delta\chi^2/\text{NDF} = 48.1/3$

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

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

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

$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2\phi_{51} + 8|U_{\mu 4} U_{e4} U_{\mu 5} U_{e5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} \overset{(+)}{-} \eta)$$

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2\phi_{41} + |U_{\alpha 5}|^2 \sin^2\phi_{51}) - 4|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2\phi_{54}$$

[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]

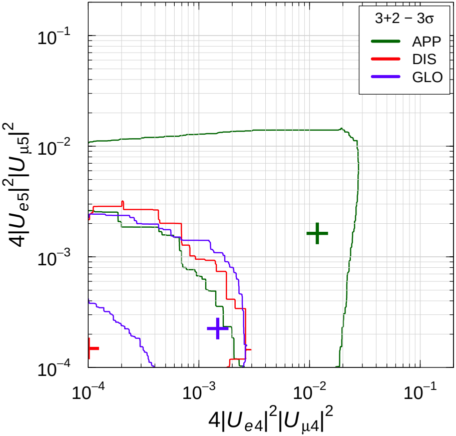
- Good: CP violation
- Bad: Two massive sterile neutrinos at the eV scale!

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

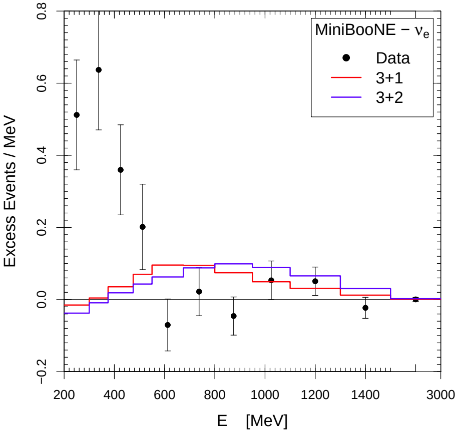
Global Fits	Our Fit		KMMS	
	3+1	3+2	3+1	3+2
GoF	5%	7%	19%	23%
PGoF	0.1%	0.04%	0.01%	0.003%

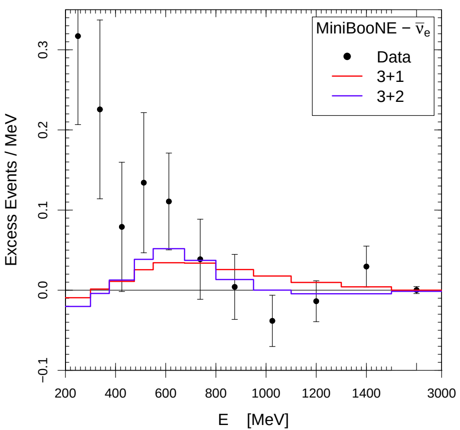
- Our Fit: 2014 update of Giunti, Laveder, Li, Long, PRD 88 (2013) 073008
- KMMS: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050

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

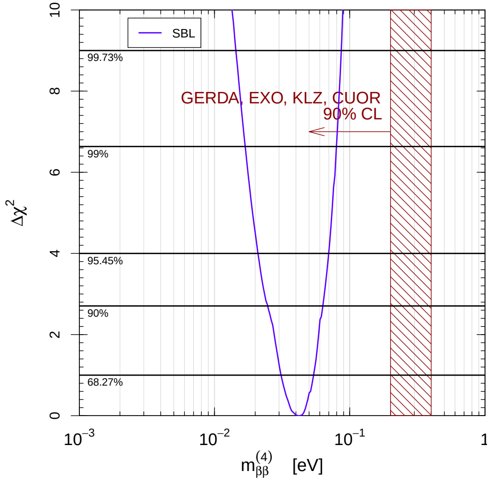
- 3+2 should be preferred to 3+1 if
  - there is consistent evidence of two peaks of the probability corresponding to two Δm^2's
  - there is CP-violating difference of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions
- MiniBooNE low-energy peak not consistent with disappearance constraints
- 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
- 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 $m_{\beta\beta}^{(3\nu-IH)}$

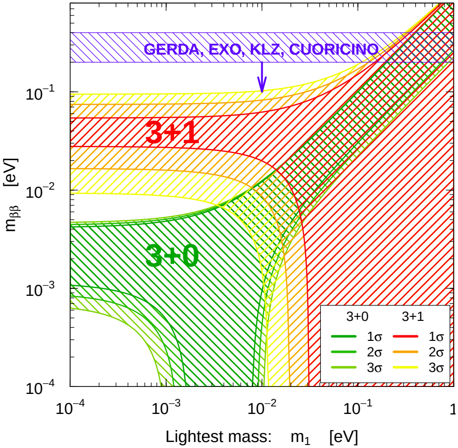
[Barry et al, JHEP 07 (2011) 091]

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

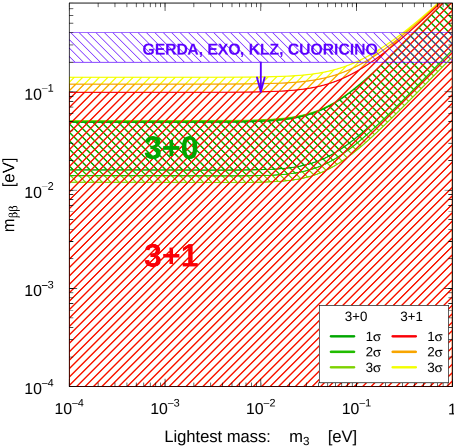
[Rodejohann, JPG 39 (2012) 124008]

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

Normal 3ν Ordering



Inverted 3ν Ordering



[Giunti, Laveder, Li, Long, 2014]

Cosmology

- neutrinos in equilibrium in early Universe through weak interactions:

$$\nu\bar{\nu} \leftrightarrows e^+e^- \qquad \overset{(-)}{\nu} e \leftrightarrows \overset{(-)}{\nu} e \qquad \overset{(-)}{\nu} N \leftrightarrows \overset{(-)}{\nu} N$$

$$\nu_e n \leftrightarrows p e^- \qquad \bar{\nu}_e p \leftrightarrows n e^+ \qquad n \leftrightarrows p e^- \bar{\nu}_e$$

- weak interactions freeze out $\Longrightarrow$ active $(\nu_e, \nu_\mu, \nu_\tau)$ neutrino decoupling

$$\Gamma_{\text{weak}} = N\sigma v \sim G_F^2 T^5 \sim T^2/M_P \sim \sqrt{G_N T^4} \sim \sqrt{G_N \rho} \sim H$$

$$T_{\nu\text{-dec}} \sim 1\,\text{MeV} \qquad t_{\nu\text{-dec}} \sim 1\,\text{s}$$

- relic neutrinos: $T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma \simeq 1.945\,\text{K} \Longrightarrow k\,T_\nu \simeq 1.676 \times 10^{-4}\,\text{eV}$ $(T_\gamma = 2.725 \pm 0.001\,\text{K})$

- number density: $n_f = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g_f T_f^3 \Longrightarrow n_{\nu_k,\bar{\nu}_k} \simeq 0.1827\, T_\nu^3 \simeq 112\,\text{cm}^{-3}$

- density contribution: $\Omega_k = \frac{n_{\nu_k,\bar{\nu}_k} m_k}{\rho_c} \simeq \frac{1}{h^2}\frac{m_k}{94\,\text{eV}} \Longrightarrow \boxed{\Omega_\nu h^2 = \frac{\sum_k m_k}{94\,\text{eV}}}$

  $\left(\rho_c = \frac{3H^2}{8\pi G_N}\right)$

[Gershtein, Zeldovich, JETP Lett. 4 (1966) 120; Cowsik, McClelland, PRL 29 (1972) 669]

- sterile neutrinos can be produced by $\nu_{e,\mu,\tau} \to \nu_s$ oscillations before active neutrino decoupling ($t_{\nu\text{-dec}} \sim 1\,\text{s}$)
- energy density of radiation before matter-radiation equality:

$$\rho_R = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right] \rho_\gamma \qquad (t < t_{\text{eq}} \sim 6 \times 10^4\,\text{y})$$

$$N_{\text{eff}}^{\text{SM}} = 3.046 \qquad \Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$$

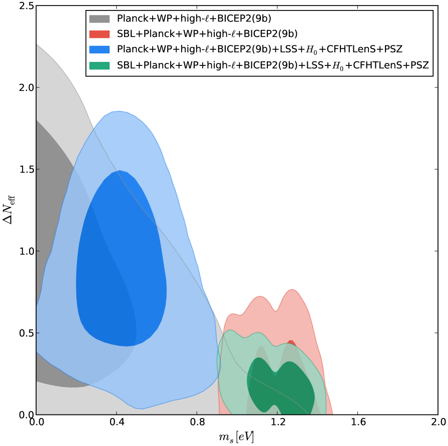
- sterile neutrino contribution:

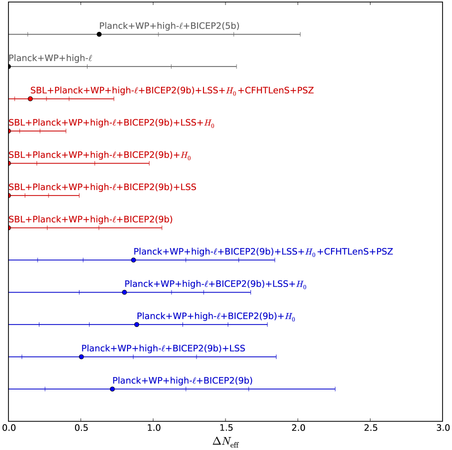
$$\rho_s = (T_s/T_\nu)^4 \rho_\nu \quad \Longrightarrow \quad \Delta N_{\text{eff}} = (T_s/T_\nu)^4$$

- sterile neutrino with mass $m_s = m_4 \simeq \sqrt{\Delta m^2_{41}} \sim 1\,\text{eV}$ becomes non-relativistic at $T_\nu \sim m_s/3$, that is at $t_{\nu_s\text{-nr}} \sim 2.0 \times 10^5\,\text{y}$, before recombination at $t_{\text{rec}} \sim 3.8 \times 10^5\,\text{y}$
- current energy density of sterile neutrinos:

$$\Omega_s = \frac{n_s m_s}{\rho_c} \simeq \frac{1}{h^2} \frac{(T_s/T_\nu)^3 m_s}{94\,\text{eV}} = \frac{1}{h^2} \frac{\Delta N_{\text{eff}}^{3/4} m_s}{94\,\text{eV}} = \frac{1}{h^2} \frac{m_s^{\text{eff}}}{94\,\text{eV}}$$

$$m_s^{\text{eff}} = \Delta N_{\text{eff}}^{3/4} m_s = (T_s/T_\nu)^3 m_s$$





[Archidiacono, Fornengo, Gariazzo, Giunti, Hannestad, Laveder, arXiv:1404.1794]

See also: [Bergstrom, Gonzalez-Garcia, Niro, Salvado, arXiv:1407.3806]

Without oscillation data:

- [Giusarma, Di Valentino, Lattanzi, Melchiorri, Mena, arXiv:1403.4852]
- [Zhang, Li, Zhang, arXiv:1403.7028]
- [Dvorkin, Wyman, Rudd, Hu, arXiv:1403.8049]
- [Zhang, Li, Zhang, arXiv:1404.3598]

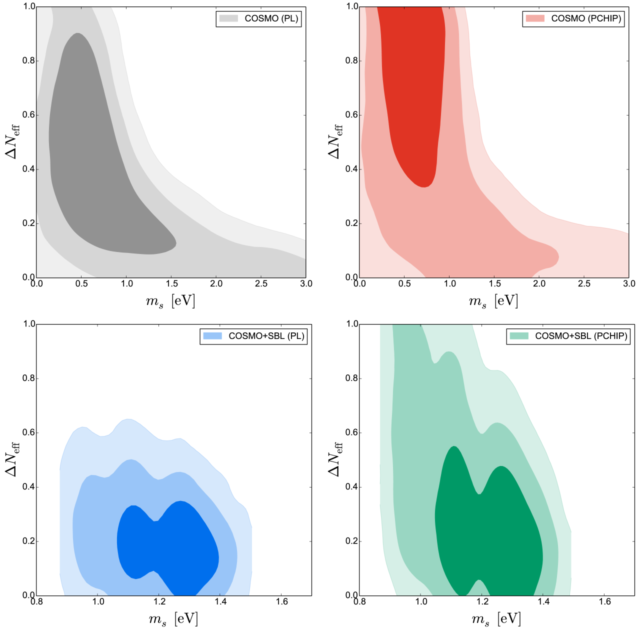
Tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1\,\text{eV}$

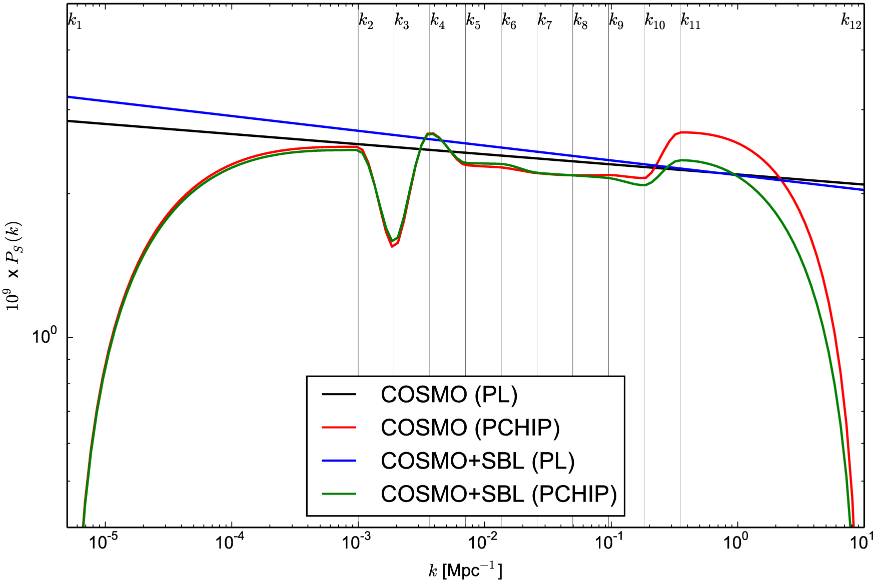
Sterile neutrinos are thermalized $(\Delta N_{\text{eff}} = 1)$ by active-sterile oscillations before neutrino decoupling [Dolgov, Villante, NPB 679 (2004) 261]

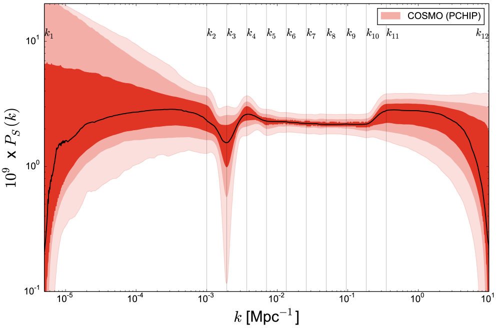
Proposed mechanisms to avoid the tension:

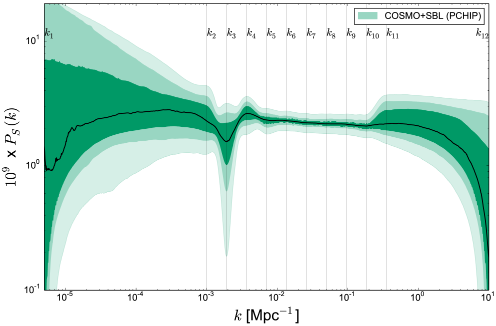
- Large lepton asymmetry [Hannestad, Tamborra, Tram, JCAP 1207 (2012) 025; Mirizzi, Saviano, Miele, Serpico, PRD 86 (2012) 053009; Saviano et al., PRD 87 (2013) 073006; Hannestad, Hansen, Tram, JCAP 1304 (2013) 032]
- Enhanced background potential due to interactions in the sterile sector [Hannestad, Hansen, Tram, PRL 112 (2014) 031802; Dasgupta, Kopp, PRL 112 (2014) 031803; Bringmann, Hasenkamp, Kersten, arXiv:1312.4947; Ko, Tang, arXiv:1404.0236; Archidiacono, Hannestad, Hansen,Tram, arXiv:1404.5915]
- A larger cosmic expansion rate at the time of sterile neutrino production [Rehagen, Gelmini JCAP 1406 (2014) 044]
- MeV dark matter annihilation [Ho, Scherrer, PRD 87 (2013) 065016]
- Free primordial power spectrum of scalar fluctuations (Inflationary Freedom) [Gariazzo, Giunti, Laveder, arXiv:1412.7405]

Inflationary Freedom




k_1
k_2
k_3
k_4
k_5
k_6
k_7
k_8
k_9
k_{10}
k_{11}
k_{12}
10^9 x $P_S(k)$
10^0
COSMO (PL)
COSMO (PCHIP)
COSMO+SBL (PL)
COSMO+SBL (PCHIP)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
k [Mpc^{-1}]


COSMO (PCHIP)
k_1 k_2 k_3 k_4 k_5 k_6 k_7 k_8 k_9 k_{10} k_{11} k_{12}
10^9 x $P_S(k)$
k [Mpc^{-1}]


COSMO+SBL (PCHIP)
k_1 k_2 k_3 k_4 k_5 k_6 k_7 k_8 k_9 k_{10} k_{11} k_{12}
10^9 x $P_S(k)$
k [Mpc^{-1}]

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.
- Cosmology:
  - Cosmological data may allow $\Delta N_{\text{eff}} \approx 1$.
  - Tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1\,\text{eV}$.
  - Cosmological and oscillation data may be reconciled by Inflationary Freedom.