Phenomenology of Light Sterile Neutrinos

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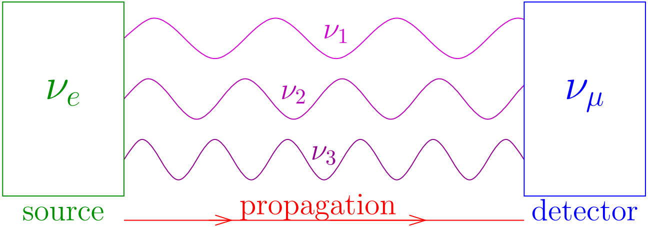
Neutrino Oscillations

- 1957: Bruno Pontecorvo proposed Neutrino Oscillations in analogy with $K^0 \leftrightarrows \bar{K}^0$ oscillations (Gell-Mann and Pais, 1955)
- 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 $\Delta m^2_{kj} \equiv m_k^2 - m_j^2$

Experimental Evidences of Neutrino Oscillations

Solar
$\nu_e \to \nu_\mu, \nu_\tau$

(SNO, BOREXino
Super-Kamiokande
GALLEX/GNO, SAGE
Homestake, Kamiokande)

VLBL Reactor
$\bar{\nu}_e$ disappearance

(KamLAND)

→ $\Delta m^2_{\mathrm{S}} \simeq 7.6 \times 10^{-5}\,\mathrm{eV}^2$
$\sin^2\vartheta_{\mathrm{S}} \simeq 0.30$

Atmospheric
$\nu_\mu \to \nu_\tau$

(Super-Kamiokande
Kamiokande, IMB
MACRO, Soudan-2)

LBL Accelerator
ν_μ disappearance

(K2K, MINOS, T2K)

LBL Accelerator
$\nu_\mu \to \nu_\tau$

(Opera)

→ $\Delta m^2_{\mathrm{A}} \simeq 2.4 \times 10^{-3}\,\mathrm{eV}^2$
$\sin^2\vartheta_{\mathrm{A}} \simeq 0.50$

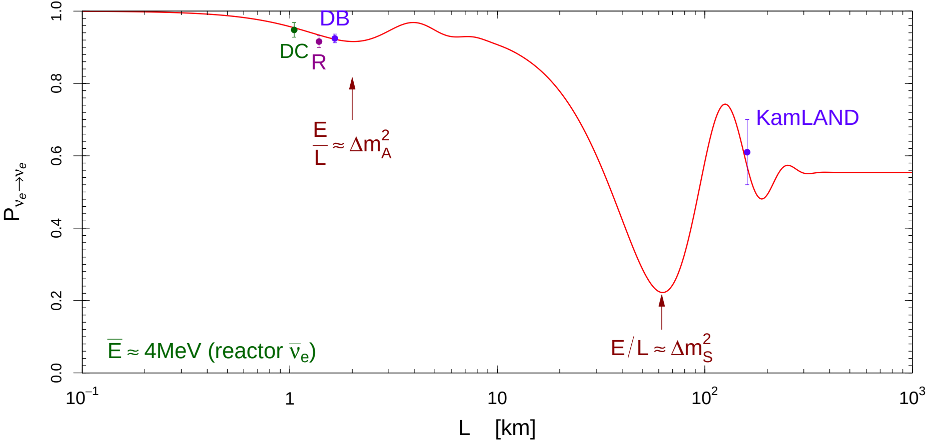
LBL Accelerator
$\nu_\mu \to \nu_e$

(T2K, MINOS)

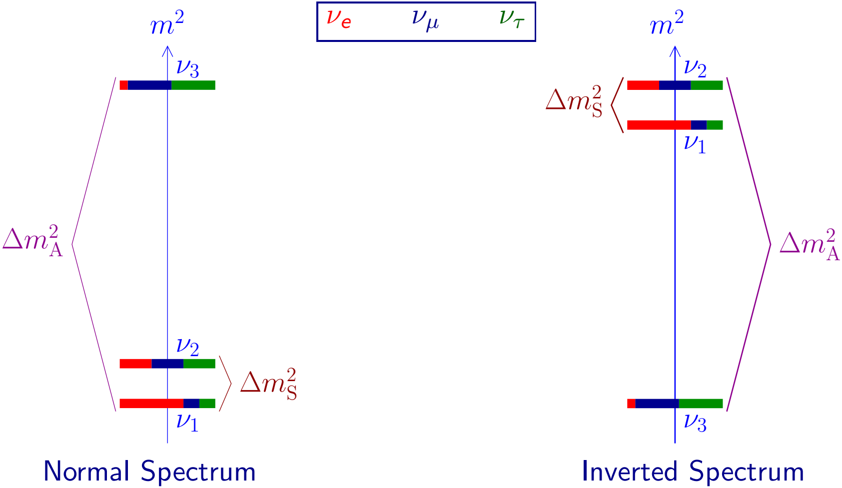
LBL Reactor
$\bar{\nu}_e$ disappearance

(Daya Bay, RENO
Double Chooz)

→ Δm^2_{A}
$\sin^2\vartheta_{13} \simeq 0.023$


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

Three-Neutrino Mixing Paradigm



different signs of $\Delta m^2_{31} \simeq \Delta m^2_{32}$

absolute scale is not determined by neutrino oscillation data

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

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

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

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\vartheta_{23}=\vartheta_{\mathrm{A}}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix}}_{\text{Daya Bay, RENO}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\vartheta_{12}=\vartheta_{\mathrm{S}}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}}_{\beta\beta_{0\nu}}$$

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

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

maximal and flat

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

Double Chooz

T2K, MINOS

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

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

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

Open Problems

- $\vartheta_{23} \lesseqgtr 45^\circ$?
  - T2K (Japan), NOνA (USA), IceCube-PINGU, INO (India), ...
- Mass Hierarchy ?
  - NOνA (USA), JUNO (China), RENO-50 (Korea), IceCube-PINGU, INO (India), ...
- CP violation ?
  - NOνA (USA), LBNE (USA), LAGUNA-LBNO (EU), 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 Mixing

- Reactor Electron Antineutrino Anomaly: $\bar{\nu}_e \to \bar{\nu}_e$

$$L \simeq 10 - 100\,\text{m} \qquad E \simeq 4\,\text{MeV}$$

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

- Gallium Anomaly: $\nu_e \to \nu_e$

$$L \simeq 1\,\text{m} \qquad E \simeq 1\,\text{MeV}$$

$$\sim 2.9\sigma \text{ deficit} \qquad \Delta m^2 \gtrsim 1\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$$

- LSND: Accelerator $\bar{\nu}_\mu \to \bar{\nu}_e$

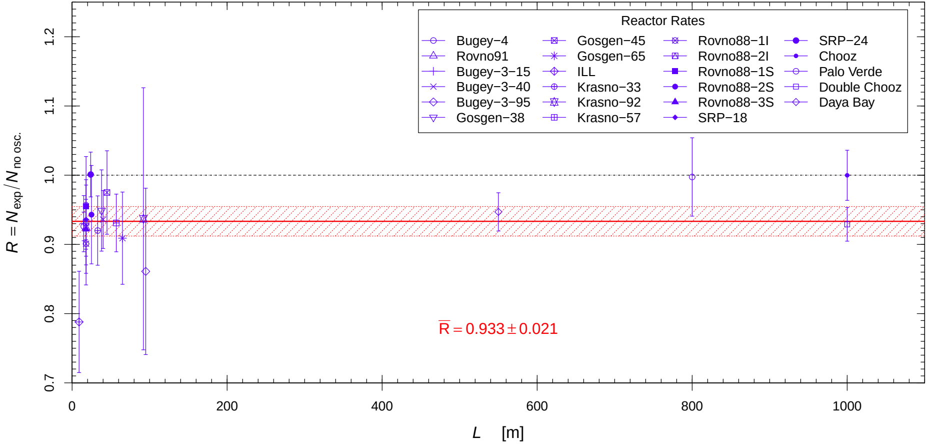
$$L \simeq 30\,\text{m} \qquad E \simeq 50\,\text{MeV}$$

$$\sim 3.8\sigma \text{ excess} \qquad \Delta m^2 \gtrsim 0.2\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$$

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; Giunti, Laveder, Li, Liu, Long, PRD 86 (2012) 113014;
Ciuffoli, Evslin, Li, JHEP 12 (2012) 110; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050;
Zhang, Qian, Vogel, PRD 87 (2013) 073018; Ivanov et al, PRC 88 (2013) 055501]

Gallium Anomaly

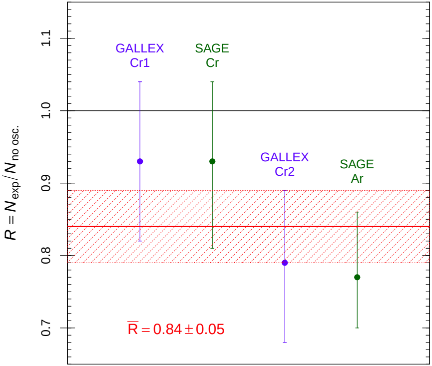
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

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]



$E \sim 0.7\,\text{MeV}$

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

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

$\sim 2.9\sigma$ anomaly

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

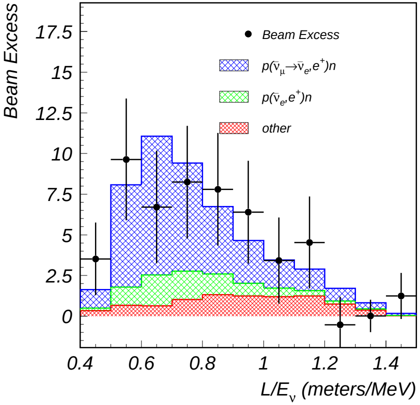
[Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344; MPLA 22 (2007) 2499; PRD 78 (2008) 073009; PRC 83 (2011) 065504; PRD 86 (2012) 113014]

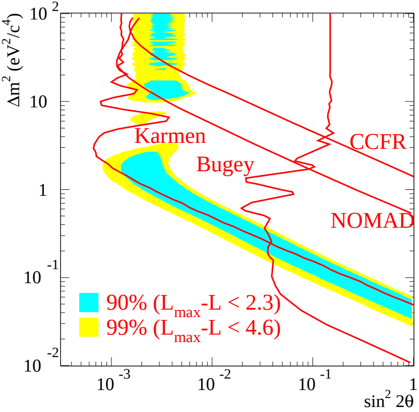
[Mention et al, PRD 83 (2011) 073006]

LSND

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

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



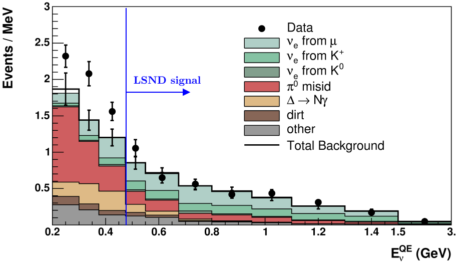


3.8σ excess $\Delta m^2_{\text{LSND}} \gtrsim 0.2\,\text{eV}^2$ $(\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

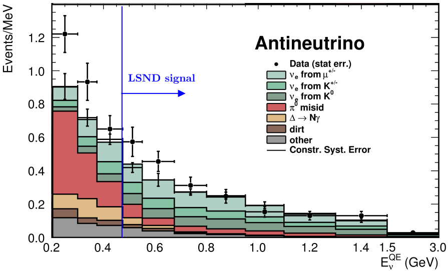
MiniBooNE

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

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



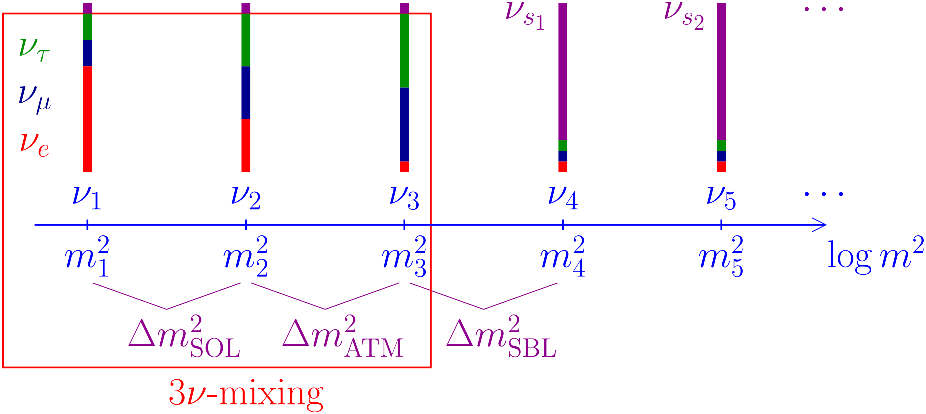
$\bar\nu_\mu \to \bar\nu_e$ [PRL 110 (2013) 161801]



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

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

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 $\sim 1\,\mathrm{eV}$ 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]

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

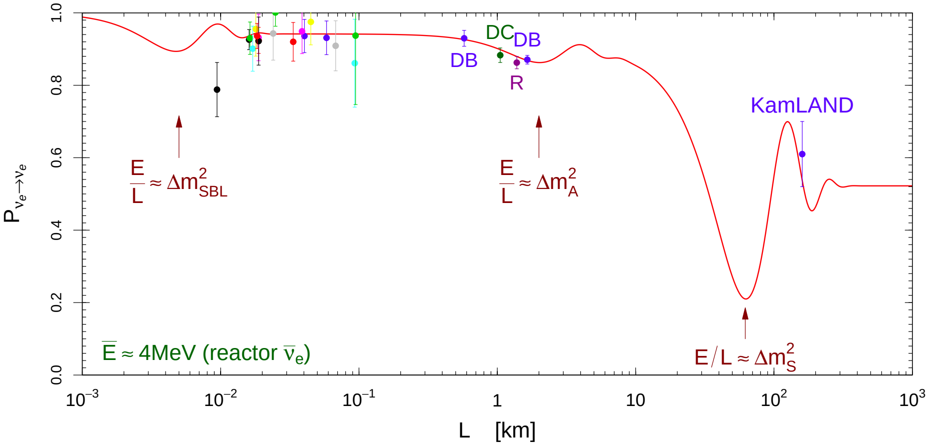
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \boxed{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \boxed{U_{\mu 4}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \boxed{U_{\tau 4}} \\ U_{s1} & U_{s2} & U_{s3} & \boxed{U_{s4}} \end{pmatrix}$$

$\uparrow$

SBL

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

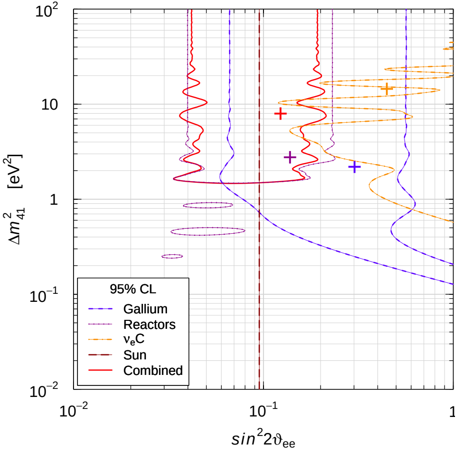
but CP violation is not observable in SBL experiments!

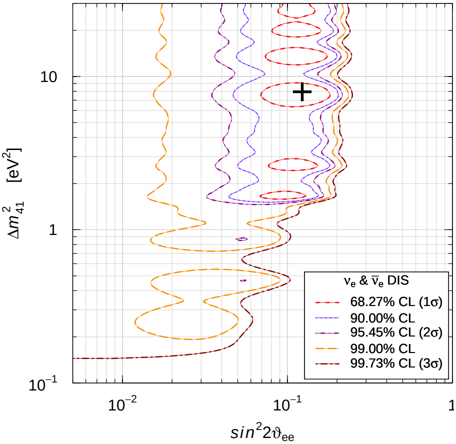


$$P^{LBL}_{\overset{(-)}{\nu_e} \to \overset{(-)}{\nu_e}} \simeq 1 - \frac{1}{2} \sin^2 2\vartheta_{14} - \cos^4 \vartheta_{14} \sin^2 2\vartheta_{13} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E} \right)$$

Global ν_e and $\bar{\nu}_e$ Disappearance

[Preliminary 2014 Update]





$\nu_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N}_{\mathrm{g.s.}} + e^-$

KARMEN + LSND

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

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

solar ν_e + KamLAND $\bar{\nu}_e$ + ϑ_{13}

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

[Palazzo, PRD 83 (2011) 113013; PRD 85 (2012) 077301]

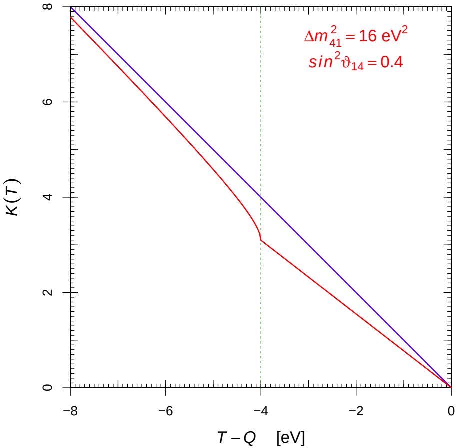
GoF = 53% PGoF = 4%

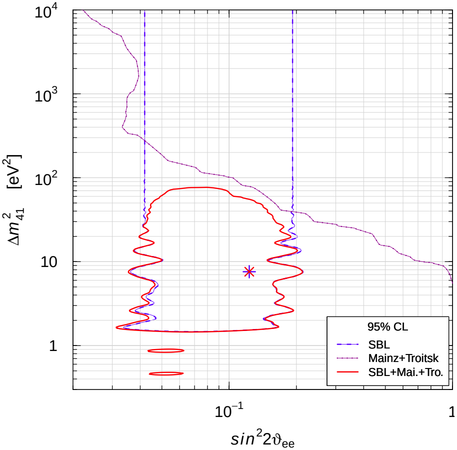
No Osc. excluded at 3.0σ

$\Delta\chi^2/\mathrm{NDF} = 11.9/2$

Mainz and Troitsk Limit on m_4^2

[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323] [Belesev et al, JETP Lett. 97 (2013) 67; JPG 41 (2014) 015001]



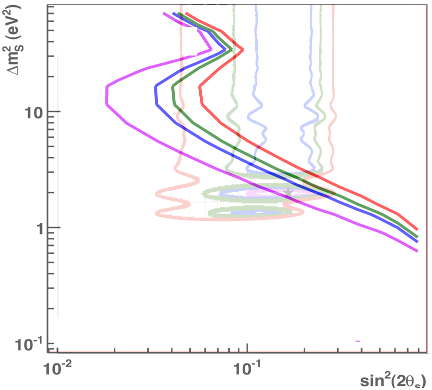


$$m_4 \gg m_1, m_2, m_3 \implies \Delta m^2_{41} \equiv m^2_4 - m^2_1 \simeq m^2_4$$

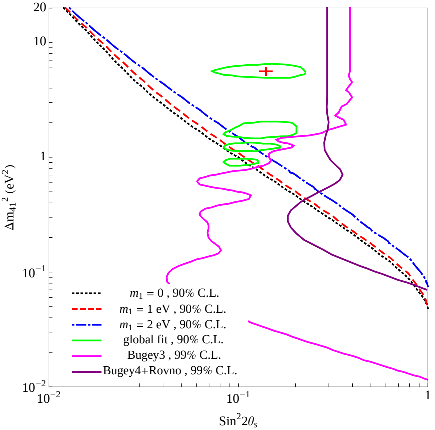
$$2\sigma: \quad 1.5 \lesssim \Delta m^2_{41} \lesssim 37\,\text{eV}^2 \implies 7\,\text{cm} \lesssim \frac{L^{\text{OSC}}_{41}}{E\,[\text{MeV}]} \lesssim 2\,\text{m}$$

[Preliminary 2014 Update]

KATRIN Sensitivity



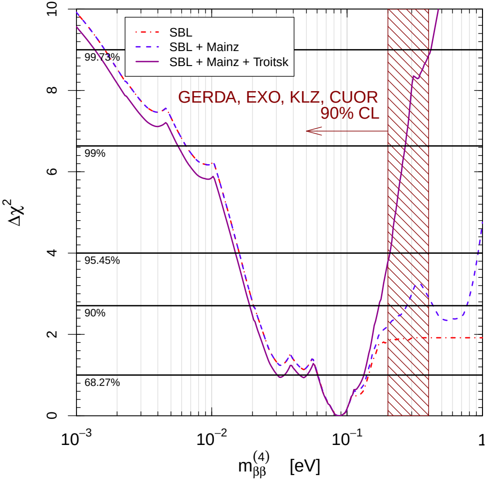
[Formaggio, Barrett, PLB 706 (2011) 68]



[Esmaili, Peres, PRD 85 (2012) 117301]

[see also: Sejersen Riis, Hannestad, JCAP (2011) 1475; Sejersen Riis, Hannestad, Weinheimer, PRC 84 (2011) 045503]

Neutrinoless Double-β Decay



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

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

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]

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:

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

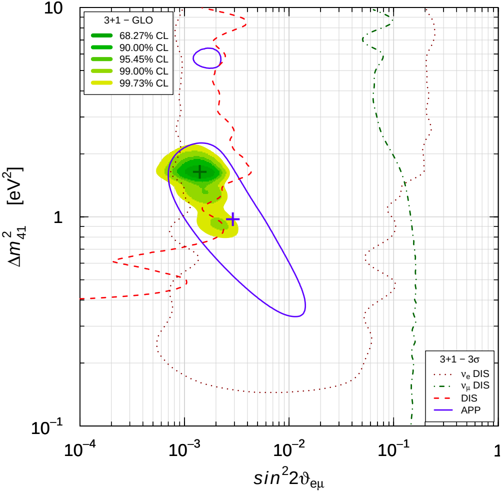
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ $\Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[Okada, Yasuda, IJMPA 12 (1997) 3669-3694]

[Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

3+1 Global Fit

[Preliminary 2014 Update]



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

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

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

No Osc. excluded at 6.3σ

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

[Giunti, Laveder, Y.F. Li, H.W. Long, PRD 88 (2013) 073008]

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

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

- 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:

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

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

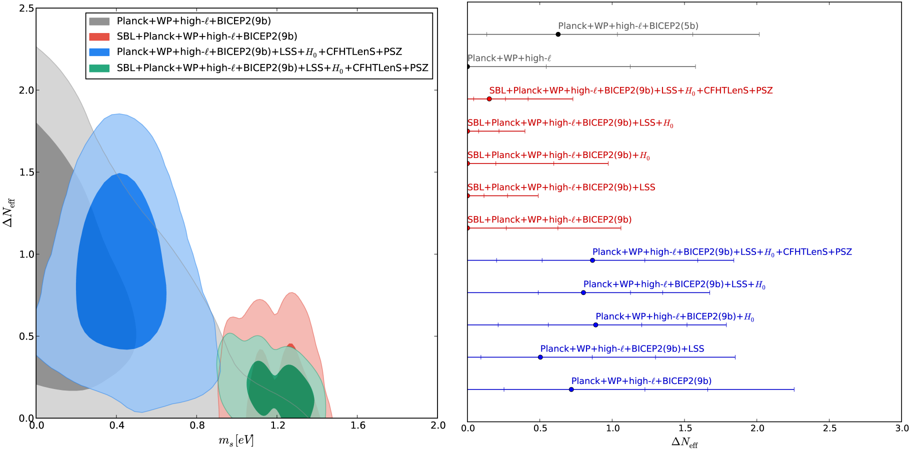
- sterile neutrino contribution:

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

- 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]

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]

Recent discussion: [Bergstrom, Gonzalez-Garcia, Niro, Salvado, arXiv:1407.3806]

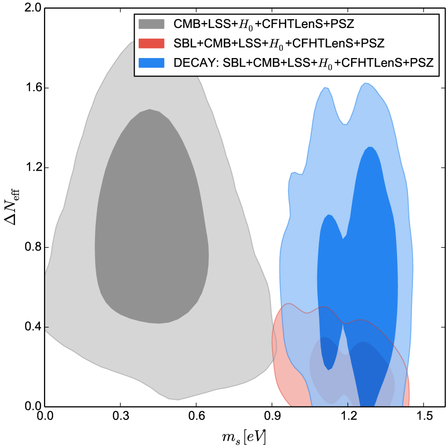
Tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1\,\text{eV}$

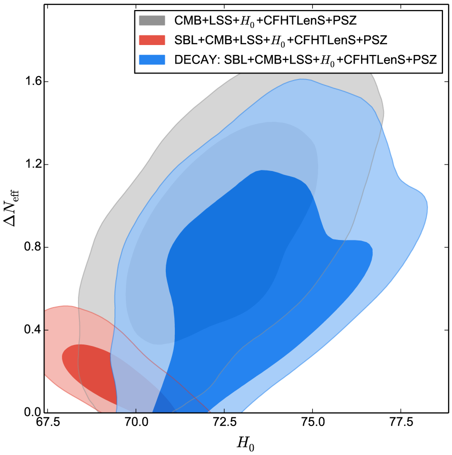
Sterile neutrinos are thermalized $(\Delta N_{\text{eff}} = 1)$ by active-sterile oscillations before neutrino decoupling [Dolgov, Villante, NPB 679 (2004) 261]

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]
- Invisible decay [Gariazzo, Giunti, Laveder, arXiv:1404.6160]

Cosmological Invisible Decay





[Gariazzo, Giunti, Laveder, arXiv:1404.6160]

$$N_s(t) = \Delta N_{\text{eff}}\, e^{-t/\tau_s} \qquad \tau_s \sim 2 \times 10^5\,\text{y}$$

Conclusions

- Short-Baseline ν_e and $\bar{\nu}_e$ 3+1 Disappearance:
  - Reactor $\bar{\nu}_e$ anomaly is alive and exciting.
  - Gallium ν_e anomaly strengthened by new cross-section measurements.
  - Many promising projects to test 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:
  - MiniBooNE experiment has been inconclusive.
  - Better experiments are needed to check LSND signal!
  - If $|U_{e4}| > 0$ why not $|U_{\mu4}| > 0$? $\Longrightarrow$ Maybe LSND luckily observed a fluctuation of a small $\bar{\nu}_\mu \to \bar{\nu}_e$ transition probability with amplitude $\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$, which has not been seen by other appearance experiments.
- Cosmology:
  - BICEP2 + Planck indication in favor of $\Delta N_{\text{eff}} \approx 1$.
  - Tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1\,\text{eV}$.
  - Cosmological and oscillation data may be explained by invisible decay of ν_s.