Phenomenology of Light Sterile Neutrinos

Carlo Giunti

INFN, Sezione di Torino, and Dipartimento di Fisica, Università di Torino
mailto://giunti@to.infn.it
Neutrino Unbound: http://www.nu.to.infn.it

Technische Universität München

Garching, München, Germany

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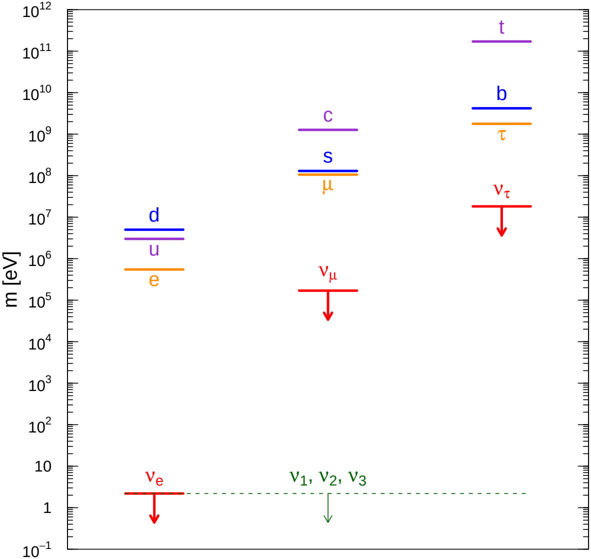
Fermion Mass Spectrum



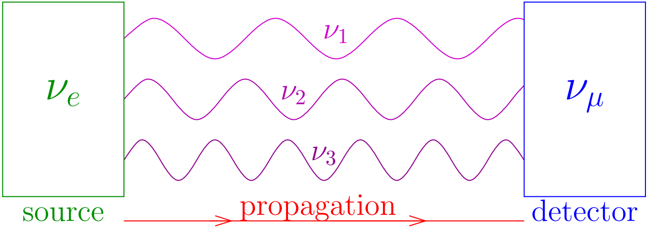
Neutrino Oscillations

- 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

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



$$|\nu(t>0)\rangle = U_{e1}\,e^{-iE_1t}\,|\nu_1\rangle + U_{e2}\,e^{-iE_2t}\,|\nu_2\rangle + U_{e3}\,e^{-iE_3t}\,|\nu_3\rangle \neq |\nu_e\rangle$$

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

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

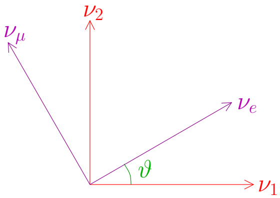
Neutrino Oscillations are Flavor Transitions

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

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

Two-Neutrino Mixing and Oscillations

$$|\nu_\alpha\rangle = \sum_{k=1}^{2} U_{\alpha k} |\nu_k\rangle \qquad (\alpha = e, \mu)$$



$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

$$\boxed{\begin{array}{l} |\nu_e\rangle = \cos\vartheta\,|\nu_1\rangle + \sin\vartheta\,|\nu_2\rangle \\ |\nu_\mu\rangle = -\sin\vartheta\,|\nu_1\rangle + \cos\vartheta\,|\nu_2\rangle \end{array}}$$

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

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

Survival Probabilities: $P_{\nu_e \to \nu_e} = P_{\nu_\mu \to \nu_\mu} = 1 - P_{\nu_e \to \nu_\mu}$

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)

$$\to \begin{cases} \Delta m^2_{\text{S}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{S}} \simeq 0.30 \end{cases}$$

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)

$$\to \begin{cases} \Delta m^2_{\text{A}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{A}} \simeq 0.50 \end{cases}$$

LBL Accelerator

$\nu_\mu \to \nu_e$

(T2K, MINOS)

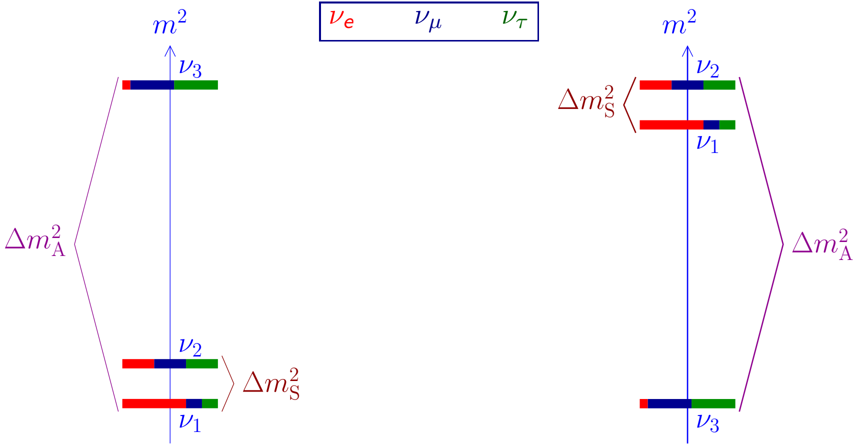
LBL Reactor

$\bar{\nu}_e$ disappearance

(Daya Bay, RENO
Double Chooz)

$$\to \begin{cases} \Delta m^2_{\text{A}} \\ \sin^2\vartheta_{13} \simeq 0.023 \end{cases}$$

Three-Neutrino Mixing Paradigm



Normal Spectrum

Inverted Spectrum

$\Delta m^2_{\mathrm{S}} = \Delta m^2_{21} = 7.50 \pm 0.20 \times 10^{-5}\,\mathrm{eV}^2$ uncertainty $\simeq 2.6\%$

$\Delta m^2_{\mathrm{A}} = |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$ uncertainty $\simeq 5\%$

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

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

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

T2K, MINOS

Daya Bay, RENO

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

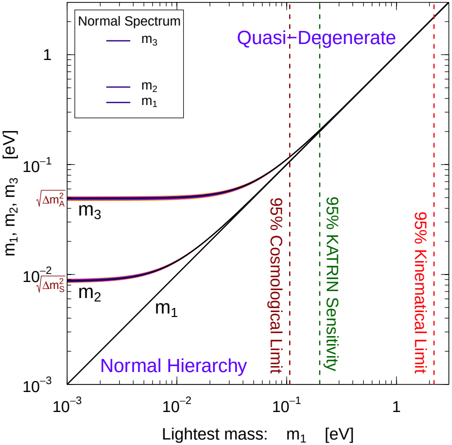
$\sin^2\vartheta_{12} = 0.30 \pm 0.01$

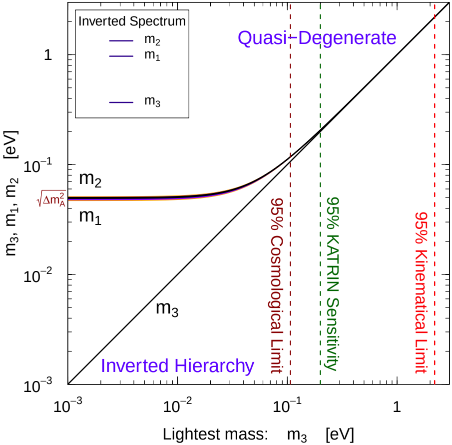
$$\frac{\delta\sin^2\vartheta_{23}}{\sin^2\vartheta_{23}} \simeq 40\% \qquad \frac{\delta\sin^2\vartheta_{13}}{\sin^2\vartheta_{13}} \simeq 10\% \qquad \frac{\delta\sin^2\vartheta_{12}}{\sin^2\vartheta_{12}} \simeq 5\%$$

Open Problems

- $\vartheta_{23} \lesseqgtr 45^\circ$?
  - Atmospheric ν, T2K, NOνA, ...
- Mass Hierarchy ?
  - NOνA, Atmospheric ν, Day Bay II, RENO-50, Supernova ν, . . .
- CP violation ?
  - NOνA, LAGUNA-LBNO, LBNE (USA), HyperK, . . .
- Absolute Mass Scale ?
  - β Decay, Neutrinoless Double-β Decay, Cosmology, . . .
- Dirac or Majorana ?
  - Neutrinoless Double-β Decay, . . .
- Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

Absolute Scale of Neutrino Masses





$$m_2^2 = m_1^2 + \Delta m^2_{21} = m_1^2 + \Delta m^2_{\mathrm{S}}$$

$$m_3^2 = m_1^2 + \Delta m^2_{31} = m_1^2 + \Delta m^2_{\mathrm{A}}$$

$$m_1^2 = m_3^2 - \Delta m^2_{31} = m_3^2 + \Delta m^2_{\mathrm{A}}$$

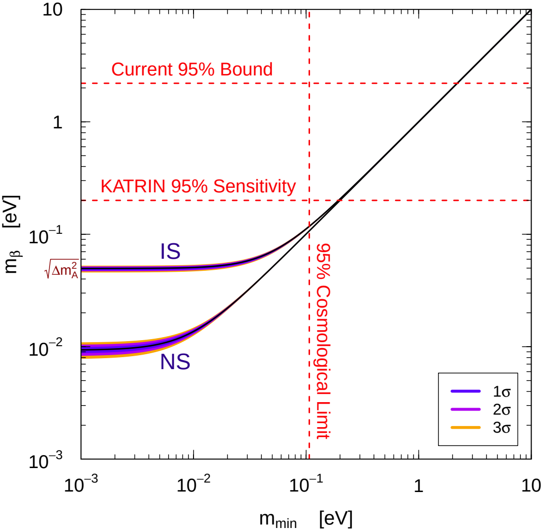
$$m_2^2 = m_1^2 + \Delta m^2_{21} \simeq m_3^2 + \Delta m^2_{\mathrm{A}}$$

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

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

Effective Neutrino Mass in Beta-Decay

$$m_\beta^2 = |U_{e1}|^2 \, m_1^2 + |U_{e2}|^2 \, m_2^2 + |U_{e3}|^2 \, m_3^2$$

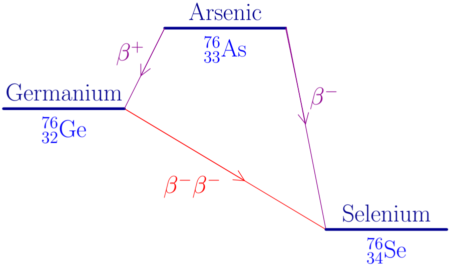


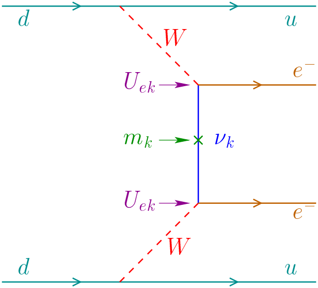
- Quasi-Degenerate:
  $$m_\beta^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2$$
- Inverted Hierarchy:
  $$m_\beta^2 \simeq (1 - s_{13}^2) \Delta m_A^2 \simeq \Delta m_A^2$$
- Normal Hierarchy:
  $$m_\beta^2 \simeq s_{12}^2 c_{13}^2 \Delta m_S^2 + s_{13}^2 \Delta m_A^2$$
  $$\simeq 2 \times 10^{-5} + 6 \times 10^{-5} \, \text{eV}^2$$
- $m_\beta \lesssim 4 \times 10^{-2} \, \text{eV}$

$\Downarrow$

Normal Spectrum

Majorana ν: Neutrinoless Double-Beta Decay





$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} \, |\mathcal{M}_{0\nu}|^2 \, m_{\beta\beta}^2$$

Effective Majorana Mass

$$\boxed{m_{\beta\beta} = \left| \sum_{k=1}^{3} U_{ek}^2 m_k \right|}$$

EXO + KamLAND-Zen

$$^{136}_{54}\mathrm{Xe} \to {}^{136}_{56}\mathrm{Ba} + e^- + e^-$$

[PRL 109 (2012) 032505; PRL 110 (2013) 062502]

$$|m_{\beta\beta}| \lesssim 0.12 - 0.25\,\mathrm{eV} \quad (90\%\mathrm{C.L.})$$

GERDA

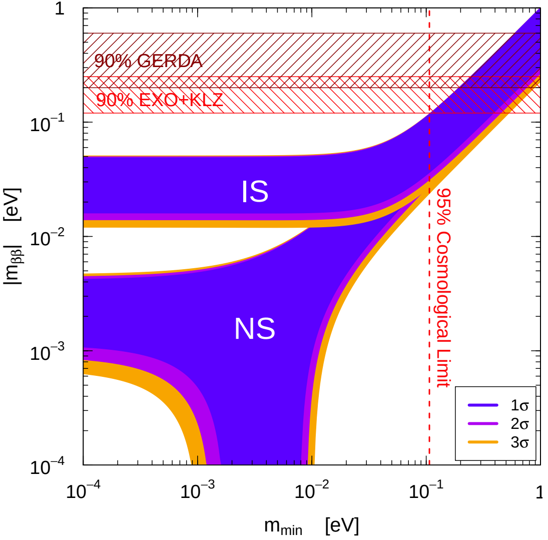
$$^{76}_{32}\mathrm{Ge} \to {}^{76}_{34}\mathrm{Se} + e^- + e^-$$

[arXiv:1307.4720]

$$|m_{\beta\beta}| \lesssim 0.2 - 0.6\,\mathrm{eV} \quad (90\%\mathrm{C.L.})$$

Effective Majorana Neutrino Mass

$$m_{\beta\beta} = |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_2}\, m_2 + |U_{e3}|^2\, e^{i\alpha_3}\, m_3$$



- Quasi-Degenerate:

$$|m_{\beta\beta}| \simeq m_\nu \sqrt{1 - s^2_{2\vartheta_{12}} s^2_{\alpha_2}}$$

- Inverted Hierarchy:

$$|m_{\beta\beta}| \simeq \sqrt{\Delta m^2_{\text{A}} (1 - s^2_{2\vartheta_{12}} s^2_{\alpha_2})}$$

- Normal Hierarchy:

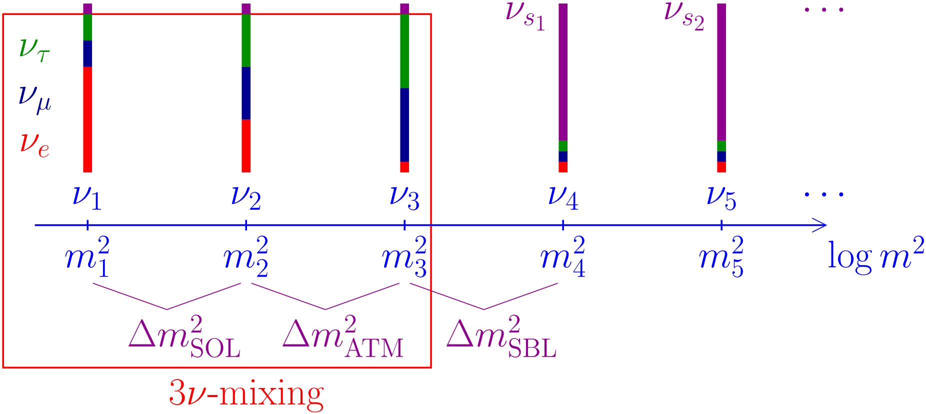
$$|m_{\beta\beta}| \simeq |s^2_{12} \sqrt{\Delta m^2_{\text{S}}} + e^{i\alpha} s^2_{13} \sqrt{\Delta m^2_{\text{A}}}|$$

$$\simeq |2.7 + 1.2 e^{i\alpha}| \times 10^{-3}\,\text{eV}$$

$m_1 \gtrsim 10^{-3}$ eV$\Rightarrow$cancellation?

$|m_{\beta\beta}| \lesssim 10^{-2}$ eV $\Longrightarrow$ Normal Spectrum

Beyond Three-Neutrino Mixing: Sterile Neutrinos



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: $L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$ $\qquad \widetilde{\Phi} = i\sigma_2\,\Phi^* = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \xrightarrow[\text{Breaking}]{\text{Symmetry}} \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$
- SM singlet $\overline{L_L}\widetilde{\Phi}$ can couple to new singlet chiral fermion field ν_R (right-handed neutrino) related to physics beyond the SM
- Known examples: SUSY, new symmetries, extra dimensions, mirror world, . . . [see `http://www.nu.to.infn.it/Sterile_Neutrinos/`]
- Dirac mass term $\sim \overline{L_L}\widetilde{\Phi}\nu_R$ $\quad + \quad$ Majorana mass term $\sim \overline{\nu_R^c}\nu_R$
- Diagonalization of mass matrix $\Longrightarrow$ massive Majorana neutrinos

Light Sterile Neutrinos

- Light anti-ν_R are called sterile neutrinos

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

- 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:

$$\begin{array}{ccccc} \multicolumn{5}{c}{\Delta m^2_{21} \ll |\Delta m^2_{31}| \ll |\Delta m^2_{41}| \le \dots} \\ \nu_1 & \nu_2 & \nu_3 & \nu_4 & \dots \\ \nu_e & \nu_\mu & \nu_\tau & \nu_{s_1} & \dots \end{array}$$

- 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]

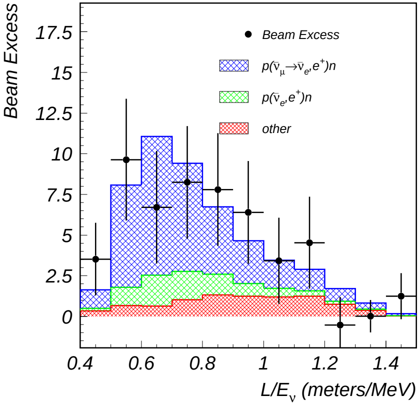
  - Heavy sterile neutrinos with mass scale $\gg 1\,\mathrm{eV}$: could be Warm Dark Matter

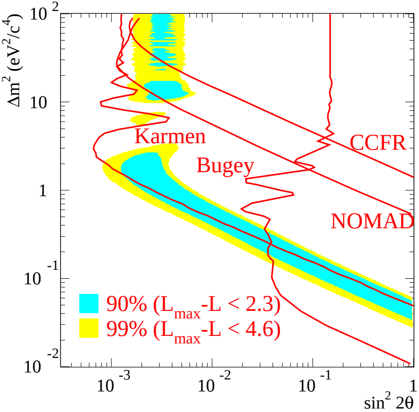
    [Kusenko, Phys. Rept. 481 (2009) 1]
    [Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191]
    [Drewes, arXiv:1303.6912]

LSND

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

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





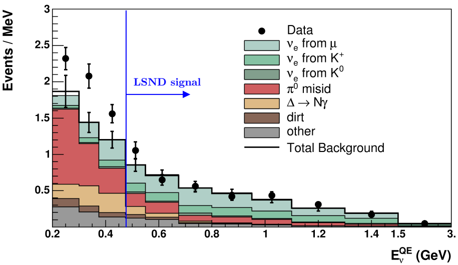
3.8σ excess $\qquad \Delta m^2_{\text{LSND}} \gtrsim 0.2\,\text{eV}^2$ $\qquad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

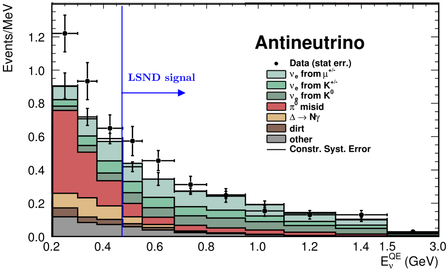
MiniBooNE

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

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

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





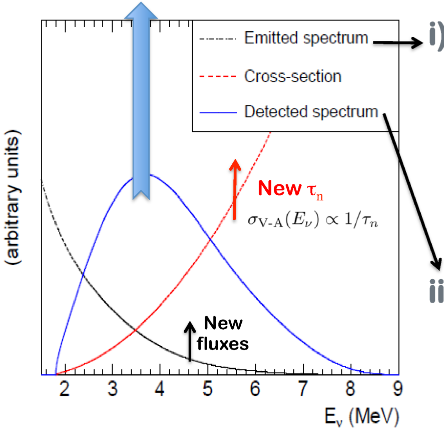
- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- LSND signal: $E > 475\,\text{MeV}$.

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

[Martini et al, PRD 85 (2012) 093012; PRD 87 (2013) 013009]

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

Increased prediction of detected flux by 6.5%



i) Neutrino Emission:

- **Improved reactor neutrino spectra → <u>+3.5%</u>**
- **Accounting for long-lived isotopes in reactors → <u>+1%</u>**

ii) Neutrino Detection:

- **Reevaluation of σ_{IBD} → <u>+1.5%</u> (evolution of the neutron life time)**
- **Reanalysis of all SBL experiments**

[T. Lasserre, TAUP 2013]

Reactor Electron Antineutrino Anomaly

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

[update in White Paper, arXiv:1204.5379]

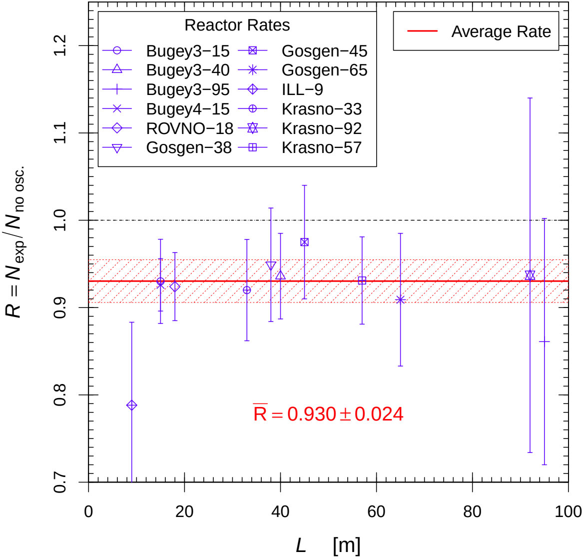
new reactor $\bar{\nu}_e$ fluxes

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

[Huber, PRC 84 (2011) 024617]

$\sim 2.8\sigma$ anomaly

[see also:
Sinev, arXiv:1103.2452;
Ciuffoli, Evslin, Li, JHEP 12 (2012) 110;
Zhang, Qian, Vogel, PRD 87 (2013) 073018;
Ivanov et al, arXiv:1306.1995]



Gallium Anomaly

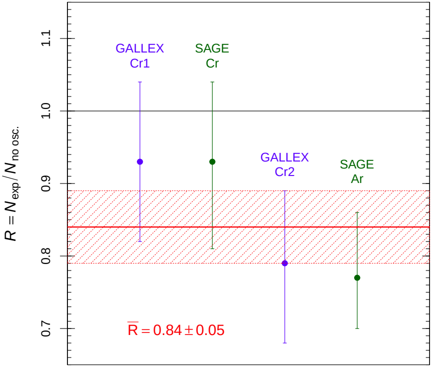
Gallium Radioactive Source Experiments: GALLEX and SAGE

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]

Effective SBL Oscillation Probabilities in 3+1 Schemes

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

No CP Violation!

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

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

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

$\uparrow$ SBL

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

$$\Downarrow$$

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

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

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

Effective SBL Oscillation Probabilities in 3+2 Schemes

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

$$\eta = \arg[U^*_{e4} U_{\mu4} U_{e5} U^*_{\mu5}]$$

$$\begin{aligned} P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = {} & 4|U_{e4}|^2 |U_{\mu4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu5}|^2 \sin^2\phi_{51} \\ & + 8|U_{\mu4}U_{e4}U_{\mu5}U_{e5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} \overset{(+)}{-} \eta) \end{aligned}$$

$$\begin{aligned} P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = {} & 1 - 4(1 - |U_{\alpha4}|^2 - |U_{\alpha5}|^2)(|U_{\alpha4}|^2 \sin^2\phi_{41} + |U_{\alpha5}|^2 \sin^2\phi_{51}) \\ & - 4|U_{\alpha4}|^2|U_{\alpha5}|^2 \sin^2\phi_{54} \end{aligned}$$

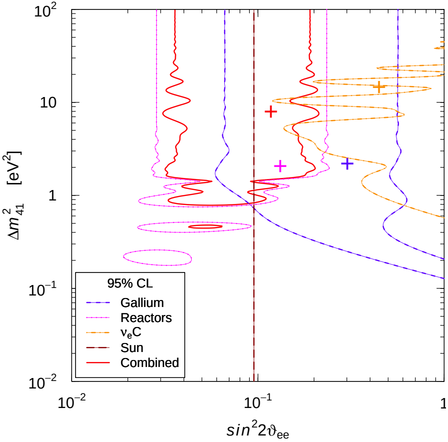
[Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004; Maltoni, Schwetz, PRD 76 (2007) 093005; Karagiorgi et al, PRD 80 (2009) 073001; Kopp, Maltoni, Schwetz, PRL 107 (2011) 091801; Giunti, Laveder, PRD 84 (2011) 073008; Donini et al, JHEP 07 (2012) 161; Archidiacono et al, PRD 86 (2012) 065028; Conrad et al, 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, arXiv:1308.5288; Girardi, Meroni, Petcov, arXiv:1308.5802]

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

  4 more parameters: $\underbrace{\Delta m^2_{41}, |U_{e4}|^2, |U_{\mu4}|^2}_{3+1}, \Delta m^2_{51}, |U_{e5}|^2, |U_{\mu5}|^2, \eta$

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

[Giunti, Laveder, Y.F. Li, Q.Y. Liu, H.W. Long, PRD 86 (2012) 113014]



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

KARMEN + LSND

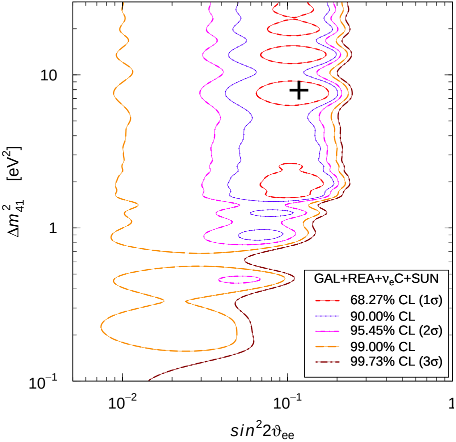
[Conrad, Shaevitz, PRD 85 (2012) 013017]

[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]



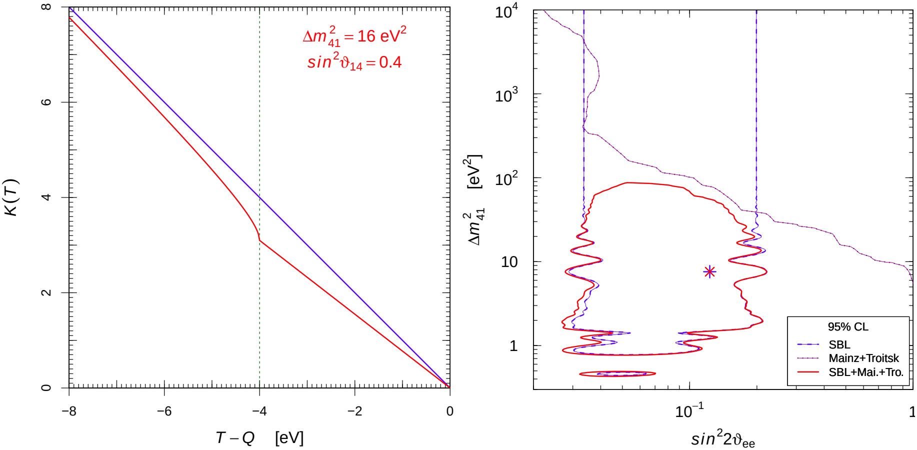
GoF = 62% PGoF = 4%

No Osc. excluded at 2.7σ

$\Delta\chi^2/\text{NDF} = 10.1/2$

Mainz and Troitsk Limit on m_4^2

[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323] [Belesev et al, JETP Lett. 97 (2013) 67; arXiv:1307.5687]

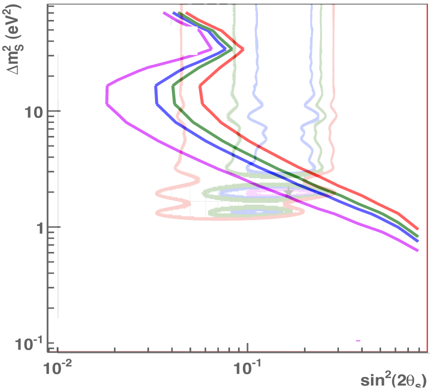


$$m_4 \gg m_1, m_2, m_3 \quad \Longrightarrow \quad \Delta m^2_{41} \equiv m_4^2 - m_1^2 \simeq m_4^2$$

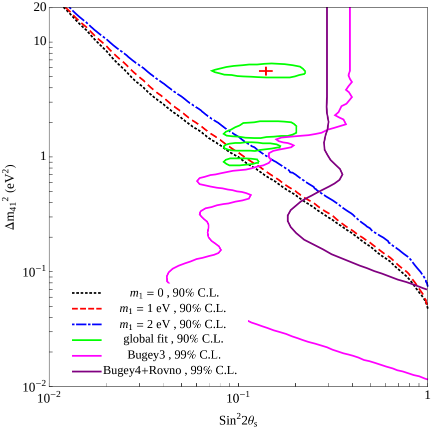
$$2\sigma: \quad 0.85 \lesssim \Delta m^2_{41} \lesssim 43\,\text{eV}^2 \quad \Longrightarrow \quad 6\,\text{cm} \lesssim \frac{L^{\text{osc}}_{41}}{E\,[\text{MeV}]} \lesssim 3\,\text{m}$$

[Giunti, Laveder, Y.F. Li, H.W. Long, PRD 87 (2013) 013004]

KATRIN Sensitivity



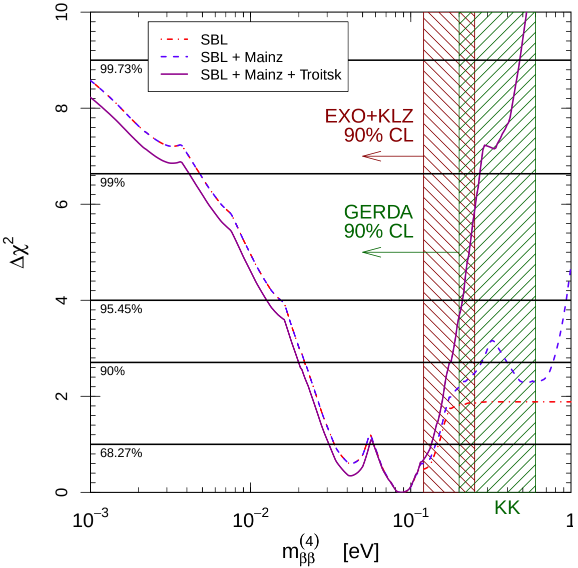
[Formaggio, Barrett, PLB 706 (2011) 68]



[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, arXiv:1308.5802]

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:

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

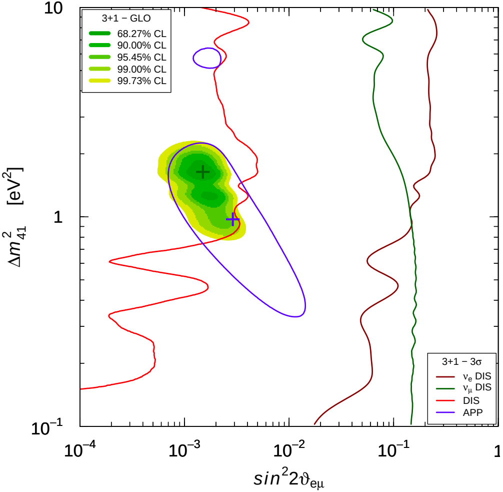
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ $\Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

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

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

3+1 Global Fit

[Giunti, Laveder, Y.F. Li, H.W. Long, arXiv:1308.5288]



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

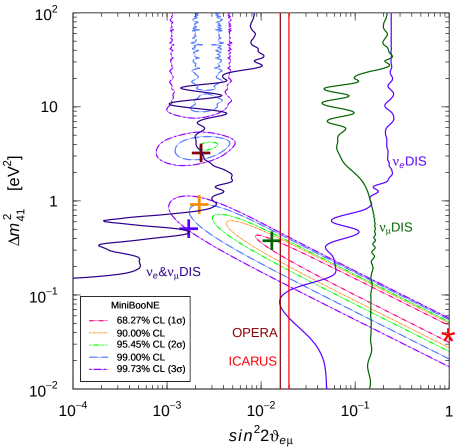
GoF = 29% PGoF = 9%

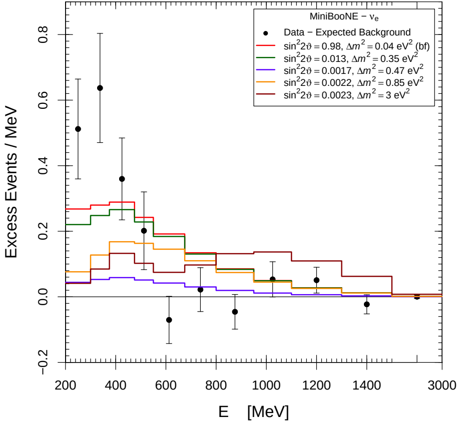
No Osc. excluded at 6.2σ

$\Delta\chi^2/\text{NDF} = 46.2/3$

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

MiniBooNE Low-Energy Excess?



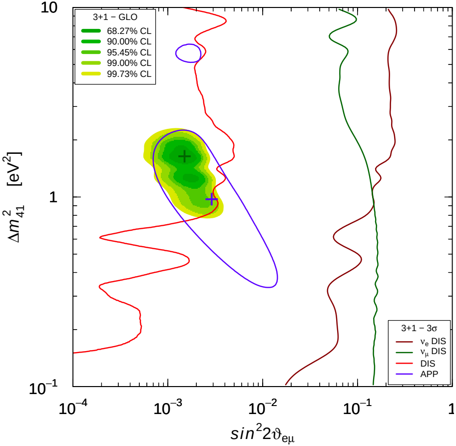


- No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 5 \times 10^{-3}$
- APP-DIS PGoF $= 0.1\%$
- Neutrino energy reconstruction problem?

[Martini, Ericson, Chanfray, PRD 85 (2012) 093012; PRD 87 (2013) 013009]

MiniBooNE Impact on SBL Oscillations?

with MiniBooNE

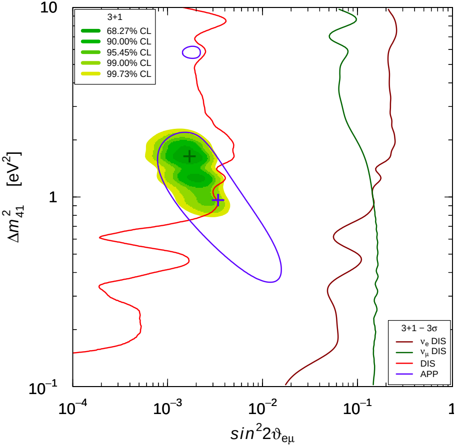


$\text{GoF} = 29\%$ $\quad$ $\text{PGoF} = 9\%$

No Osc. excluded at 6.2σ

$\Delta\chi^2/\text{NDF} = 46.2/3$

without MiniBooNE



$\text{GoF} = 19\%$ $\quad$ $\text{PGoF} = 8\%$

No Osc. excluded at 6.3σ

$\Delta\chi^2/\text{NDF} = 47.1/3$

Without LSND: No Osc. excluded only at 2.1σ $\quad$ $(\Delta\chi^2/\text{NDF} = 8.3/3)$

3+2

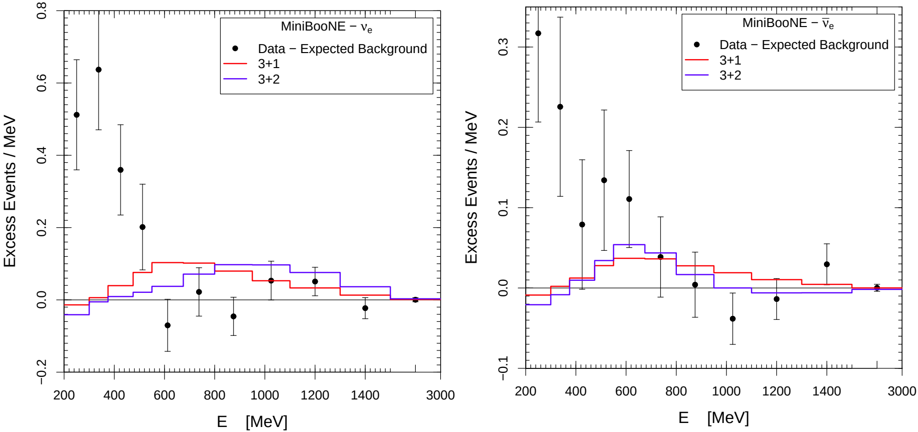
- 3+2 should be preferred to 3+1 only if
  - there is evidence of two peaks of the probability corresponding to two Δm^2's

    or
  - there is CP-violating difference of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions
- 2008 ν + 2010 $\bar{\nu}$ MiniBooNE data indicated ν–$\bar{\nu}$ difference

  $\Downarrow$

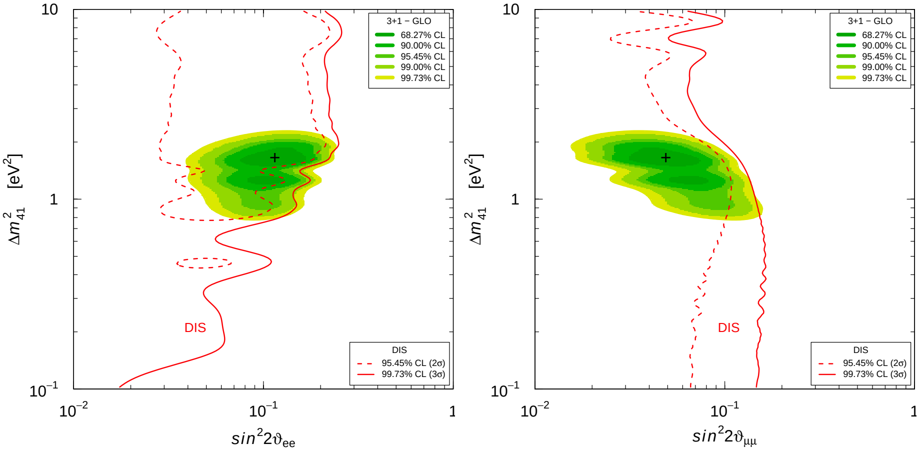
  reasonable and useful to consider 3+2
- ν–$\bar{\nu}$ difference almost disappeared with 2012 $\bar{\nu}$ data
- Okkam razor: 3+1 is enough!
- Different approach and conclusions:
  - Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050:
    Use all MiniBooNE data. No 3+1 global fit. 3+2 slightly preferred? Small allowed region.
  - Conrad, Ignarra, Karagiorgi, Shaevitz, Spitz, AHEP 2013 (2013) 163897:
    Use all MiniBooNE data. 3+2 strongly preferred. Very small allowed regions.

MiniBooNE Low-Energy Excess?



- 3+1: GoF = 6% PGoF = 0.2%
- 3+2: GoF = 8% PGoF = 0.1%

ν_e and ν_μ Disappearance



Many Exciting New Experiments and Projects

- Reactor $\bar{\nu}_e$ Disappearance:
  - Nucifer (OSIRIS, Saclay), Stereo (ILL, Grenoble) [arXiv:1204.5379]
  - DANSS (Kalinin Nuclear Power Plant, Russia) [arXiv:1304.3696], POSEIDON (PIK, Gatchina, Russia) [arXiv:1204.2449]
  - SCRAAM (San Onofre, California) [arXiv:1204.5379]
  - CARR (China Advanced Research Reactor) [arXiv:1303.0607]
  - Neutrino-4 (SM-3, Dimitrovgrad, Russia), SOLID (BR2, Belgium), Hanaro (Korea) [D. Lhuillier, EPSHEP 2013]
- Radioactive Source ν_e and $\bar{\nu}_e$ Disappearance:
  - SOX (Borexino, Gran Sasso, Italy) [arXiv:1304.7721]
  - CeLAND (^{144}Ce@KamLAND, Japan) [arXiv:1107.2335]
  - SAGE (Baksan, Russia) [arXiv:1006.2103]
  - IsoDAR (DAEδALUS, USA) [arXiv:1210.4454, arXiv:1307.2949]
  - SNO+, Daya Bay, RENO [T. Lasserre, Neutrino 2012]
- Accelerator $\overset{(-)}{\nu}_{\mu} \to \overset{(-)}{\nu}_{e}$ Appearance:
  - ICARUS/NESSIE (CERN) [arXiv:1304.2047, arXiv:1306.3455]
  - nuSTORM [arXiv:1308.0494]
  - OscSNS (Oak Ridge, USA) [arXiv:1305.4189, arXiv:1307.7097]

Effects of light sterile neutrinos can be also seen in:

- Solar neutrinos

  [Dooling et al, PRD 61 (2000) 073011, Gonzalez-Garcia et al, PRD 62 (2000) 013005;
  Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301;
  Li et al, PRD 80 (2009) 113007, PRD 87, 113004 (2013), JHEP 1308 (2013) 056;
  Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

- Atmospheric neutrinos

  [Goswami, PRD 55 (1997) 2931;
  Bilenky, Giunti, Grimus, Schwetz, PRD 60 (1999) 073007;
  Maltoni, Schwetz, Tortola, Valle, NPB 643 (2002) 321, PRD 67 (2003) 013011;
  Choubey, JHEP 12 (2007) 014;
  Razzaque, Smirnov, JHEP 07 (2011) 084, PRD 85 (2012) 093010;
  Gandhi, Ghoshal, PRD 86 (2012) 037301;
  Esmaili, Halzen, Peres, JCAP 1211 (2012) 041;
  Esmaili, Smirnov, arXiv:1307.6824]

- Supernova neutrinos

  [Caldwell, Fuller, Qian, PRD 61 (2000) 123005;
  Peres, Smirnov, NPB 599 (2001);
  Sorel, Conrad, PRD 66 (2002) 033009;
  Tamborra, Raffelt, Huedepohl, Janka, JCAP 1201 (2012) 013;
  Wu, Fischer, Martinez-Pinedo, Qian, arXiv:1305.2382]

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:
  - Important effects of sterile neutrinos.
  - Implications depend on theoretical framework and considered data set.
  - Cosmological indications must be checked by laboratory experiments.