Short-Baseline Neutrino Oscillation Anomalies and Light Sterile Neutrinos

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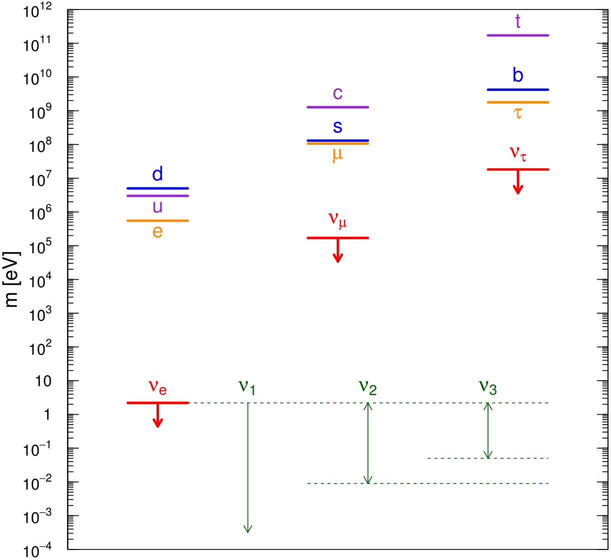
Fermion Mass Spectrum



Neutrino Mixing

Left-handed Flavor Neutrinos produced in Weak Interactions

$$|\nu_e, -\rangle \qquad |\nu_\mu, -\rangle \qquad |\nu_\tau, -\rangle$$

$$\mathcal{H}_{CC} = \frac{g}{\sqrt{2}} W_\rho \left(\overline{\nu_{eL}} \gamma^\rho e_L + \overline{\nu_{\mu L}} \gamma^\rho \mu_L + \overline{\nu_{\tau L}} \gamma^\rho \tau_L \right) + \text{H.c.}$$

Fields $\nu_{\alpha L} = \sum_k U_{\alpha k} \nu_{kL} \quad \Longrightarrow \quad |\nu_\alpha, -\rangle = \sum_k U_{\alpha k}^* |\nu_k, -\rangle$ States

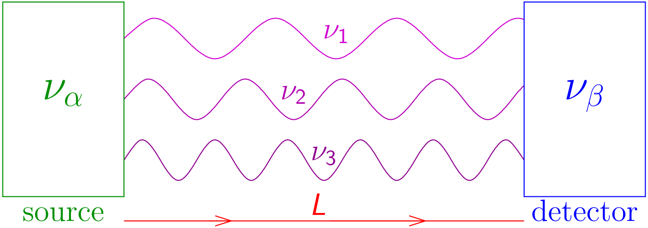
$$|\nu_1, -\rangle \qquad |\nu_2, -\rangle \qquad |\nu_3, -\rangle$$

Left-handed Massive Neutrinos propagate from Source to Detector

3×3 Unitary Mixing Matrix: $U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$

Neutrino Oscillations

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = U_{\alpha 1}^* \, |\nu_1\rangle + U_{\alpha 2}^* \, |\nu_2\rangle + U_{\alpha 3}^* \, |\nu_3\rangle$$



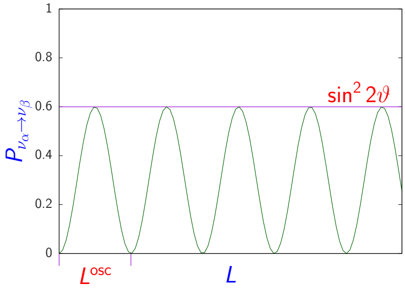
$$|\nu(t>0)\rangle = U_{\alpha 1}^* \, e^{-iE_1 t} \, |\nu_1\rangle + U_{\alpha 2}^* \, e^{-iE_2 t} \, |\nu_2\rangle + U_{\alpha 3}^* \, e^{-iE_3 t} \, |\nu_3\rangle \neq |\nu_\alpha\rangle$$

$$E_k^2 = p^2 + m_k^2 \qquad\qquad t = L$$

$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\beta | \nu(L) \rangle|^2 = \sum_{k,j} U_{\beta k} \, U_{\alpha k}^* \, U_{\beta j}^* \, U_{\alpha j} \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E} \right)$$

the oscillation probabilities depend on U and $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$

2ν-mixing: $P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \implies L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}$



Tiny neutrino masses lead to observable macroscopic oscillation distances!

$$\frac{L}{E} \lesssim \begin{cases} 10 \, \frac{\text{m}}{\text{MeV}} \, \left(\frac{\text{km}}{\text{GeV}}\right) & \text{short-baseline experiments} & \Delta m^2 \gtrsim 10^{-1} \, \text{eV}^2 \\ 10^3 \, \frac{\text{m}}{\text{MeV}} \, \left(\frac{\text{km}}{\text{GeV}}\right) & \text{long-baseline experiments} & \Delta m^2 \gtrsim 10^{-3} \, \text{eV}^2 \\ 10^4 \, \frac{\text{km}}{\text{GeV}} & \text{atmospheric neutrino experiments} & \Delta m^2 \gtrsim 10^{-4} \, \text{eV}^2 \\ 10^{11} \, \frac{\text{m}}{\text{MeV}} & \text{solar neutrino experiments} & \Delta m^2 \gtrsim 10^{-11} \, \text{eV}^2 \end{cases}$$

Neutrino oscillations are the optimal tool to reveal tiny neutrino masses!

Three-Neutrino Mixing Paradigm

Standard Parameterization of Mixing Matrix (as CKM)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{13}} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta_{13}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta_{13}} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{13}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta_{13}} & c_{23} c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$c_{ab} \equiv \cos\vartheta_{ab}$ $\quad s_{ab} \equiv \sin\vartheta_{ab}$ $\quad 0 \leq \vartheta_{ab} \leq \frac{\pi}{2}$ $\quad 0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$

OSCILLATION PARAMETERS

- 3 Mixing Angles: ϑ_{12}, ϑ_{23}, ϑ_{13}
- 1 CPV Dirac Phase: δ_{13}
- 2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: Δm^2_{21}, Δm^2_{31}

2 CPV Majorana Phases: λ_{21}, λ_{31} $\iff$ $|\Delta L| = 2$ processes

Three-Neutrino Mixing Ingredients

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

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

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

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

(KamLAND)

$\to$

$$\Delta m^2_{\text{S}} = \Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\text{eV}^2$$

$$\sin^2\vartheta_{\text{S}} = \sin^2\vartheta_{12} \simeq 0.30$$

Three-Neutrino Mixing Ingredients

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

Atmospheric $\nu_\mu \to \nu_\tau$	(Super-Kamiokande Kamiokande, IMB MACRO, Soudan-2)
LBL Accelerator ν_μ disappearance	(K2K, MINOS T2K, NOνA)
LBL Accelerator $\nu_\mu \to \nu_\tau$	(OPERA)

$$\rightarrow \begin{cases} \Delta m^2_{\mathrm{A}} \simeq |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2 \\ \sin^2 \vartheta_{\mathrm{A}} = \sin^2 \vartheta_{23} \simeq 0.50 \end{cases}$$

Three-Neutrino Mixing Ingredients

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

LBL Accelerator
$\nu_\mu \to \nu_e$ (T2K, MINOS, NOνA)

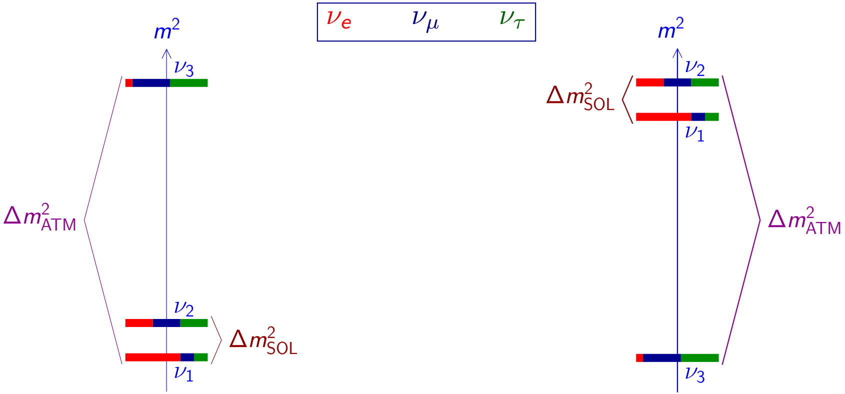
LBL Reactor
$\bar{\nu}_e$ disappearance (Daya Bay, RENO, Double Chooz)

$\to$

$$\Delta m^2_{\text{A}} \simeq |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\text{eV}^2$$

$$\sin^2 \vartheta_{13} \simeq 0.022$$

Mass Ordering



Normal Ordering

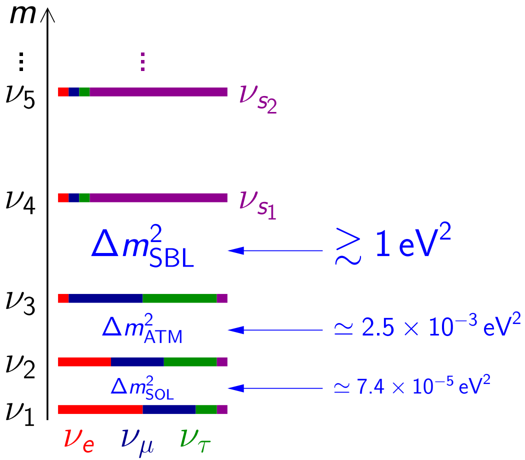
$\Delta m^2_{31} > \Delta m^2_{32} > 0$

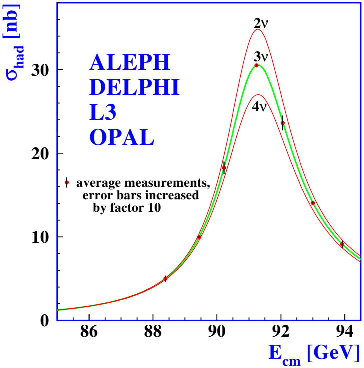
Inverted Ordering

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

absolute scale is not determined by neutrino oscillation data

Beyond Three-Neutrino Mixing: Sterile Neutrinos





$$N_{\nu_{active}}^{LEP} = 2.9840 \pm 0.0082$$

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
- Active left-handed neutrinos can mix with non-SM singlet fermions often called right-handed neutrinos
- Light left-handed anti-ν_R are light 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:

$$\Delta m^2_{21} \ll |\Delta m^2_{31}| \ll |\Delta m^2_{41}| \le \ldots$$

ν_1	ν_2	ν_3	ν_4	$\ldots$
ν_e	ν_μ	ν_τ	ν_{s_1}	$\ldots$

- Here 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

    [de Holanda, Smirnov, PRD 69 (2004) 113002; PRD 83 (2011) 113011]

    [Das, Pulido, Picariello, PRD 79 (2009) 073010]

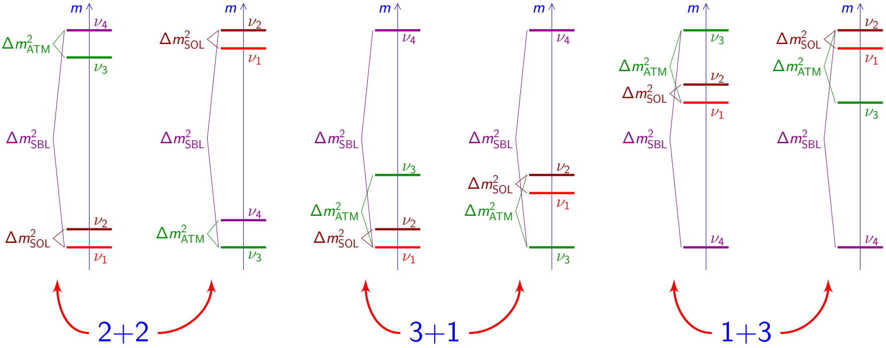
    Recent Daya Bay constraints for $10^{-3} \lesssim \Delta m^2 \lesssim 10^{-1}\,\text{eV}^2$ [PRL 113 (2014) 141802]

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

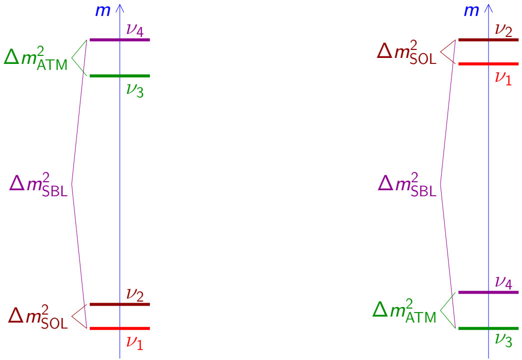
    [Asaka, Blanchet, Shaposhnikov, PLB 631 (2005) 151; Asaka, Shaposhnikov, PLB 620 (2005) 17; Asaka, Shaposhnikov, Kusenko, PLB 638 (2006) 401; Asaka, Laine, Shaposhnikov, JHEP 0606 (2006) 053, JHEP 0701 (2007) 091]

    [Reviews: 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]

Four-Neutrino Schemes: 2+2, 3+1 and 1+3



2+2 Four-Neutrino Schemes

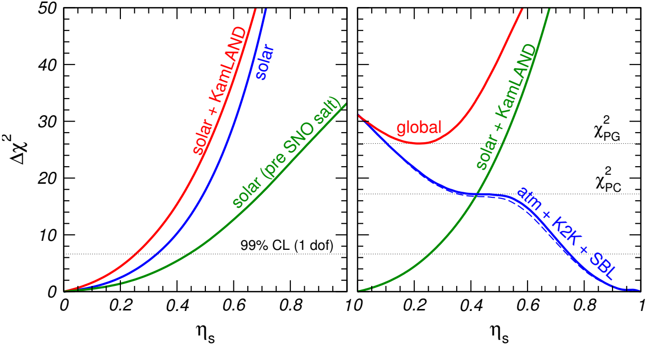


- After LSND (1995) 2+2 was preferred to 3+1, because of the 3+1 appearance-disappearance tension

  [Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]

- This is not a perturbation of 3-ν Mixing $\Longrightarrow$ Large active–sterile oscillations for solar or atmospheric neutrinos!

2+2 Schemes are Strongly Disfavored



Solar: Matter Effects + SNO NC

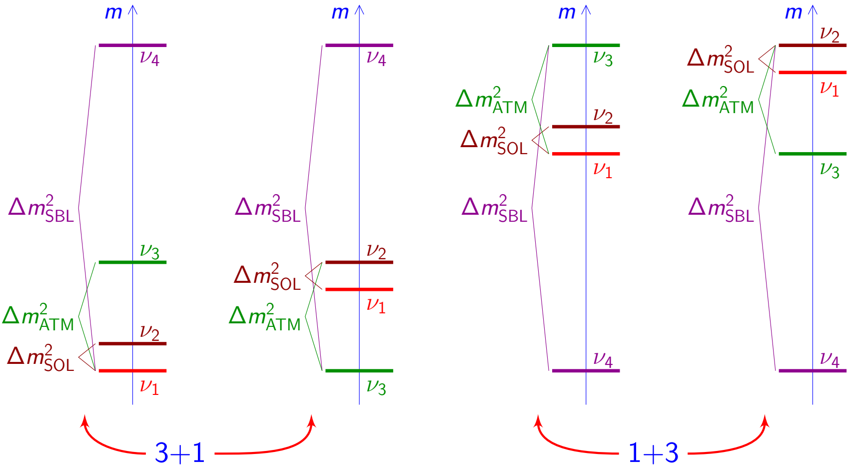
Atmospheric: Matter Effects

$$\eta_s = |U_{s1}|^2 + |U_{s2}|^2 = 1 - |U_{s3}|^2 + |U_{s4}|^2$$

$$\text{99\% CL:} \quad \begin{cases} \eta_s < 0.25 & \text{(Solar + KamLAND)} \\ \eta_s > 0.75 & \text{(Atmospheric + K2K)} \end{cases}$$

[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122]

3+1 and 1+3 Four-Neutrino Schemes



- Perturbation of 3-ν Mixing: $|U_{e4}|^2, |U_{\mu4}|^2, |U_{\tau4}|^2 \ll 1 \quad |U_{s4}|^2 \simeq 1$
- 1+3 schemes are disfavored by cosmology (ΛCDM):

$$\sum_{k=1}^{3} m_k \lesssim 0.2\,\text{eV}$$ [Planck, Astron. Astrophys. 594 (2016) A13 (arXiv:1502.01589)]

Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

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

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

Disappearance

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

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

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

SBL

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

- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to Δm^2_{ATM} [de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142; Kayser et al, JHEP 1511 (2015) 039, JHEP 1611 (2016) 122] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, CG, PRD 87, 113004 (2013) 113004]

Common Parameterization of 4×4 Mixing Matrix

$$U = \left[W^{34} R^{24} W^{14} R^{23} W^{13} R^{12} \right] \mathrm{diag}\left(1, e^{i\lambda_{21}}, e^{i\lambda_{31}}, e^{i\lambda_{41}}\right)$$

$$= \begin{pmatrix} c_{12}c_{13}c_{14} & s_{12}c_{13}c_{14} & c_{14}s_{13}e^{-i\delta_{13}} & s_{14}e^{-i\delta_{14}} \\ \cdots & \cdots & \cdots & c_{14}s_{24} \\ \cdots & \cdots & \cdots & c_{14}c_{24}s_{34}e^{-i\delta_{34}} \\ \cdots & \cdots & \cdots & c_{14}c_{24}c_{34} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 & 0 \\ 0 & 0 & e^{i\lambda_{31}} & 0 \\ 0 & 0 & 0 & e^{i\lambda_{41}} \end{pmatrix}$$

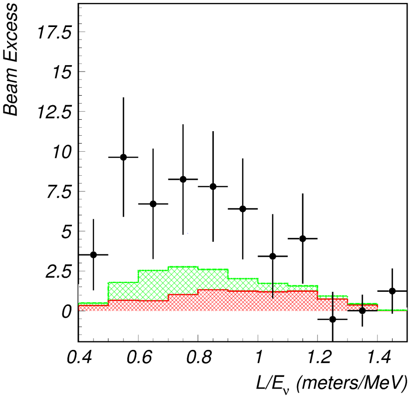
$$|U_{e4}|^2 = \sin^2\vartheta_{14} \quad \Rightarrow \quad \sin^2 2\vartheta_{ee} = 4|U_{e4}|^2\left(1 - |U_{e4}|^2\right) = \sin^2 2\vartheta_{14}$$

$$|U_{\mu4}|^2 = \cos^2\vartheta_{14}\sin^2\vartheta_{24} \simeq \sin^2\vartheta_{24} \Rightarrow \sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2\left(1 - |U_{\mu4}|^2\right) \simeq \sin^2 2\vartheta_{24}$$

LSND

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

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad$ $20\,\text{MeV} \le E \le 52.8\,\text{MeV}$



$\Delta m^2_{\text{SBL}} \gtrsim 0.1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$

- Well-known and pure source of $\bar{\nu}_\mu$

$$\underset{800\,\text{MeV}}{p} + \text{target} \to \pi^+ \xrightarrow{\text{at rest}} \mu^+ + \nu_\mu$$

$$\mu^+ \xrightarrow[\text{at rest}]{} e^+ + \nu_e + \bar{\nu}_\mu$$

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

$$\bar{\nu}_e + p \to n + e^+$$

Well-known detection process of $\bar{\nu}_e$

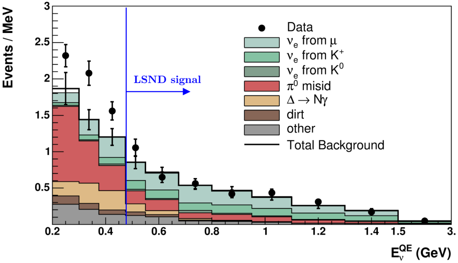
- $\approx 3.8\sigma$ excess
- But signal not seen by KARMEN at $L \simeq 18\,\text{m}$ with the same method

[PRD 65 (2002) 112001]

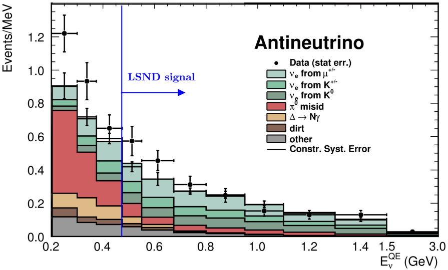
MiniBooNE

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

$\nu_\mu \to \nu_e$ [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).
- No money, no Near Detector.
- LSND signal: $E > 475\,\text{MeV}$.
- Agreement with LSND signal?
- Low-energy anomaly $\Rightarrow$ MicroBooNE
- Pragmatic Approach: $E > 475\,\text{MeV}$.

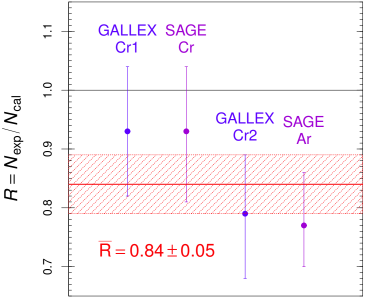
Gallium Anomaly

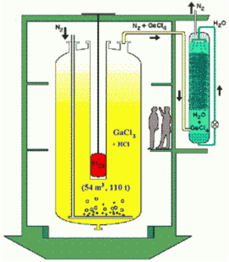
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

$E \simeq 0.75\,\text{MeV}$ $\quad E \simeq 0.81\,\text{MeV}$

Test of Solar ν_e Detection: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$





$\approx 2.9\sigma$ deficit

$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m}$ $\quad \langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$

$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$

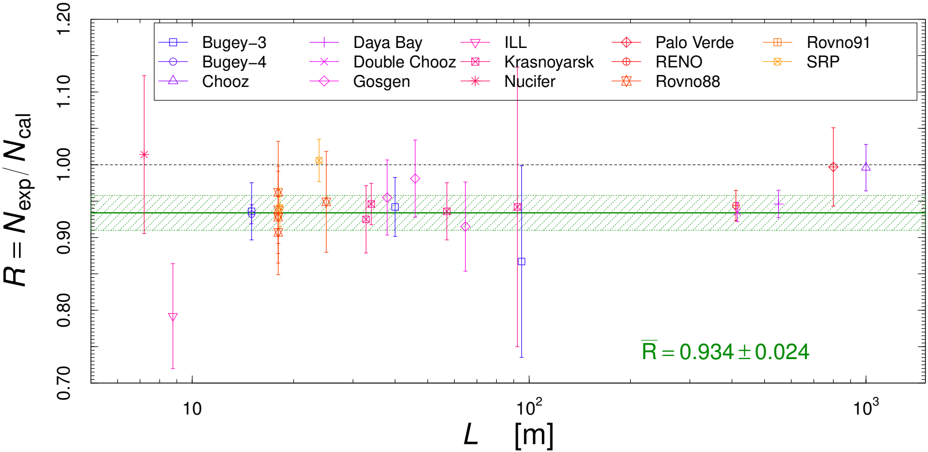
[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807; Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344, MPLA 22 (2007) 2499, PRD 78 (2008) 073009, PRC 83 (2011) 065504]

- ${}^3\text{He} + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + {}^3\text{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]

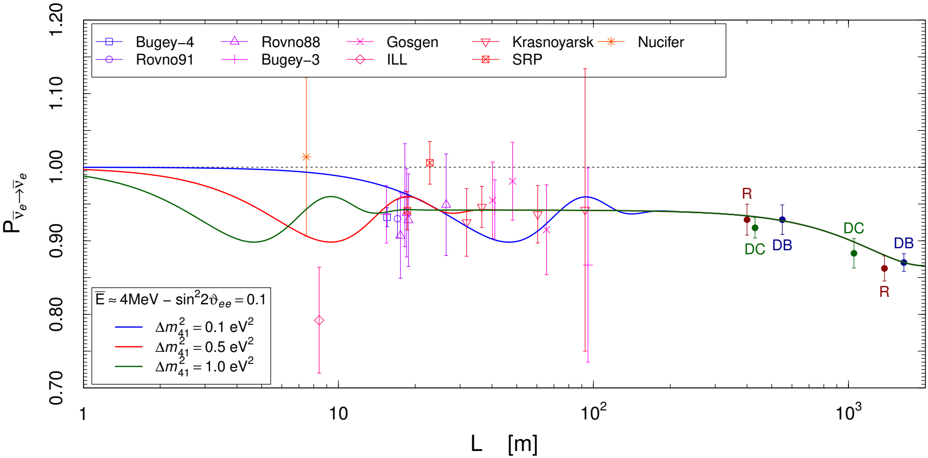
Reactor Electron Antineutrino Anomaly

[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]



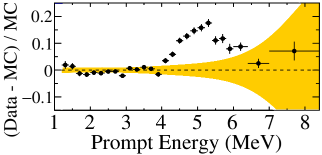
$\approx 2.8\sigma$ deficit



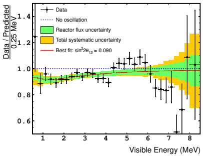
$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$$

- SBL oscillations are averaged at the Daya Bay, RENO, and Double Chooz near detectors $\Longrightarrow$ no spectral distortion

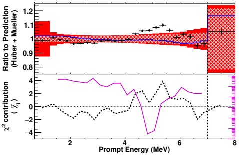
Reactor Antineutrino 5 MeV Bump



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]

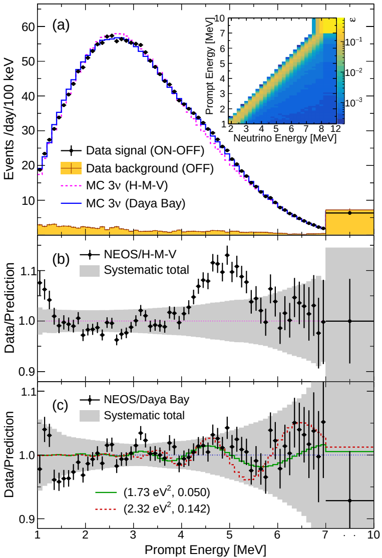


[Daya Bay, arXiv:1508.04233]

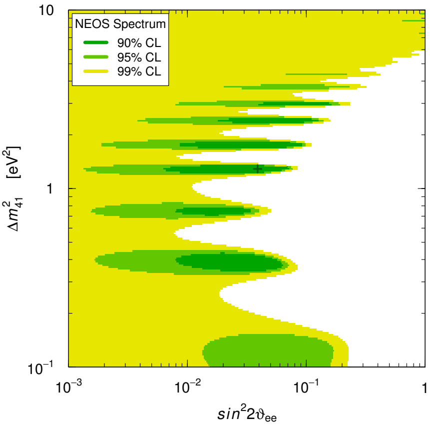
- Cannot be explained by neutrino oscillations (SBL oscillations are averaged in Double Chooz, Daya Bay, RENO).
- It is likely due to theoretical miscalculation of the spectrum.
- $\sim 3\%$ effect on total flux, but if it is an excess it increases the anomaly!
- No post-bump complete calculation of the neutrino fluxes.
- Saclay-Huber flux calculation uncertainty is about 2.5%.
- Increasing the flux uncertainty is a game that one can play, but there are only guesses, e.g. about 5%. [Hayes and Vogel, 2016]
- Increasing the flux uncertainty decreases the statistical significance of the anomaly, but more anomaly is allowed in combined fits with other data!
- At the moment it is better to consider the calculated flux and uncertainties in order to predict the signal that must be tested in new experiments.

NEOS

[PRL 118 (2017) 121802 (arXiv:1610.05134)]



- Hanbit Nuclear Power Complex in Yeong-gwang, Korea.
- Thermal power of 2.8 GW.
- Detector: a ton of Gd-loaded liquid scintillator in a gallery approximately 24 m from the reactor core.
- The measured antineutrino event rate is 1976 per day with a signal to background ratio of about 22.



Best Fits:

$\Delta m^2_{41} = 1.7\,\text{eV}^2 \quad \sin^2 2\theta_{14} = 0.05$

$\Delta m^2_{41} = 1.3\,\text{eV}^2 \quad \sin^2 2\theta_{14} = 0.04$

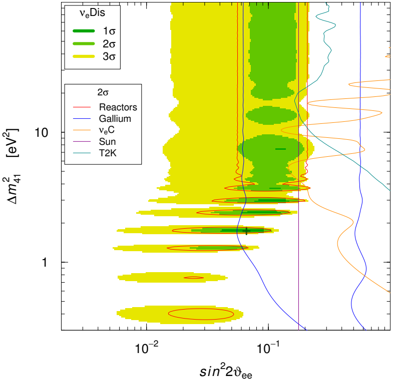
$\chi^2_{\text{no osc.}} - \chi^2_{\text{min}} = 6.5$

χ^2 distribution: $\approx 2.1\sigma$ anomaly

NEOS Monte Carlo: $\approx 1.2\sigma$ anomaly

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

[Gariazzo, CG, Laveder, Li, JHEP 1706 (2017) 135 (arXiv:1703.00860)]



$$L_{41}^{\text{OSC}} = \frac{4\pi E}{\Delta m^2_{41}}$$

- KARMEN+LSND ν_e–^{12}C
  [Conrad, Shaevitz, PRD 85 (2012) 013017]
  [CG, Laveder, PLB 706 (2011) 20]
- Solar ν_e + KamLAND $\bar{\nu}_e$
  [Li et al, PRD 80 (2009) 113007, PRD 86 (2012) 113014]
  [Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301]
- T2K Near Detector ν_e disappearance
  [T2K, PRD 91 (2015) 051102]
- $\Delta\chi^2_{\text{NO}}/\text{NDF}_{\text{NO}} = 14.1/2 \Rightarrow \approx 3.3\sigma$ anom.
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$
  $\sin^2 2\vartheta_{ee} = 0.066 \quad \Leftrightarrow \quad |U_{e4}|^2 = 0.017$
- $\chi^2_{\text{min}}/\text{NDF} = 163.0/174 \Rightarrow \text{GoF} = 71\%$

In agreement with Dentler, Hernandez-Cabezudo, Kopp, Maltoni, Schwetz, arXiv:1709.04294

Tritium Beta-Decay: $^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_e$

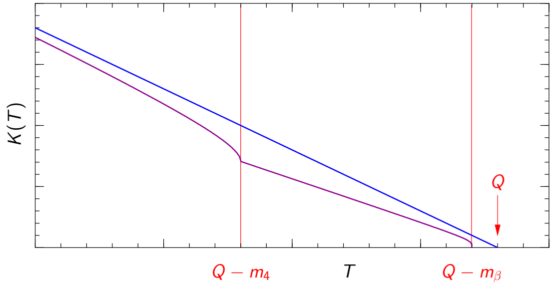
$$Q = M_{^3\text{H}} - M_{^3\text{He}} - m_e = 18.58\,\text{keV}$$

$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, p\, E\, K^2(T)$$

$$\frac{K^2(T)}{Q-T} = \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2}\, \theta(Q - T - m_k)$$

$$m_4 \gg m_{1,2,3} \Rightarrow \simeq \left(1 - |U_{e4}|^2\right) \sqrt{(Q-T)^2 - m_\beta^2}\, \theta(Q - T - m_\beta)$$

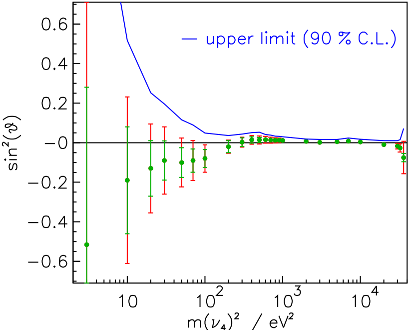
$$+ |U_{e4}|^2 \sqrt{(Q-T)^2 - m_4^2}\, \theta(Q - T - m_4)$$



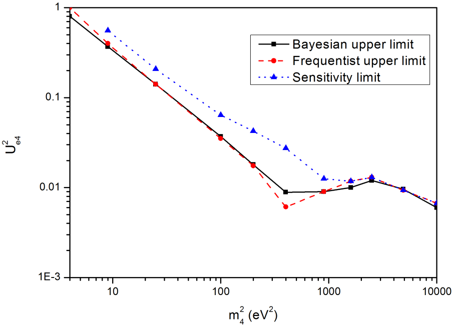
$$m_\beta^2 = \sum_{k=1}^{3} |U_{ek}|^2 m_k^2$$

Mainz and Troitsk Limit on $\Delta m^2_{41} \simeq m^2_4$

$$m_4 \gg m_{1,2,3} \quad \Longrightarrow \quad \Delta m^2_{41} \equiv m^2_4 - m^2_1 \simeq m^2_4$$



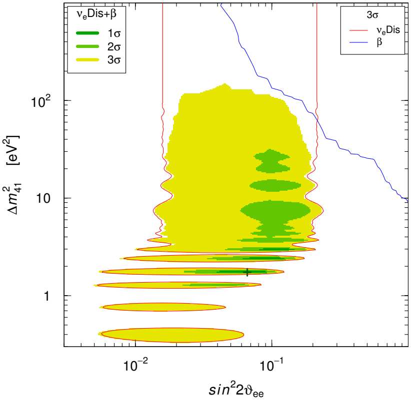
[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323]



[Belesev et al, JPG 41 (2014) 015001]

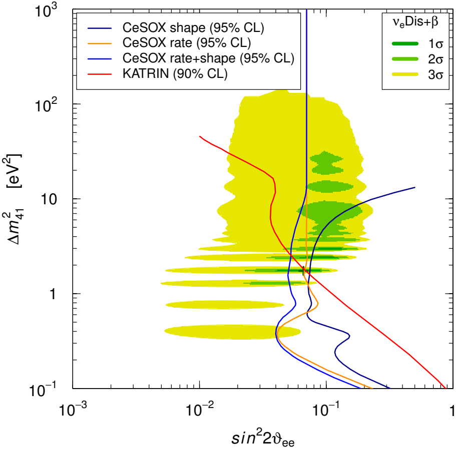
Global ν_e and $\bar{\nu}_e$ Disappearance + β Decay

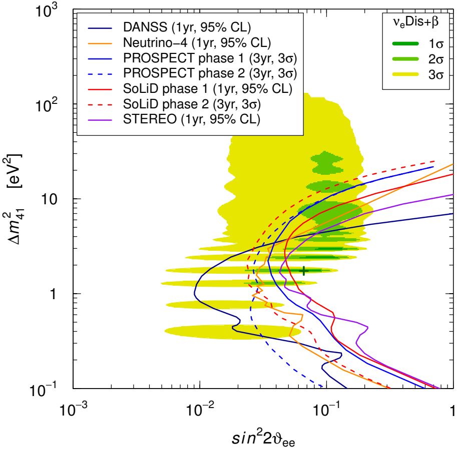
[Gariazzo, CG, Laveder, Li, JHEP 1706 (2017) 135 (arXiv:1703.00860)]



- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$
  $\sin^2 2\vartheta_{ee} = 0.066 \quad \Leftrightarrow \quad |U_{e4}|^2 = 0.017$
- $2\,\text{cm} \lesssim \dfrac{L^{\text{osc}}_{41}}{E\,[\text{MeV}]} \lesssim 7\,\text{m}$ at 3σ
- $0.0050 \lesssim \sin^2 2\vartheta_{ee} \lesssim 0.23$ at 3σ

The Race for ν_e and $\bar{\nu}_e$ Disappearance



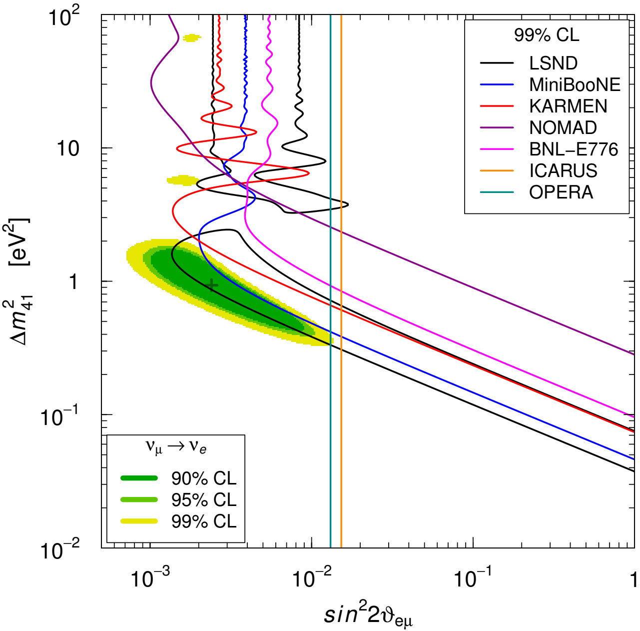


CeSOX (Gran Sasso, Italy) $^{144}Ce \to \bar{\nu}_e$
BOREXINO: $L \simeq$ 5-12m [Vivier@TAUP2015]

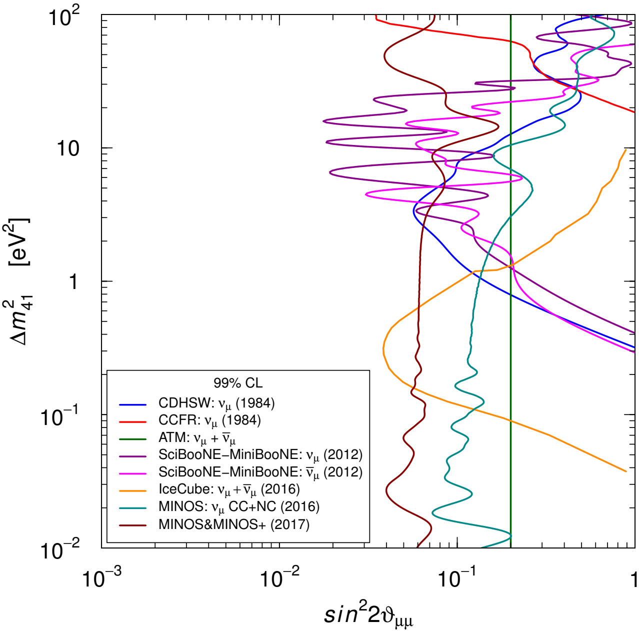
KATRIN (Karlsruhe, Germany) $^{3}H \to \bar{\nu}_e$
[Drexlin@NOW2016]

DANSS (Kalinin, Russia) $L \simeq$ 10-12m [arXiv:1606.02896]
Neutrino-4 (RIAR, Russia) $L \simeq$ 6-11m [JETP 121 (2015) 578]
PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]
SoLid (SCK-CEN, Belgium) $L \simeq$ 5-8m [arXiv:1510.07835]
STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]

$\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ Appearance



ν_μ and $\bar{\nu}_\mu$ Disappearance



3+1 Appearance-Disappearance Tension

ν_e DIS

$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

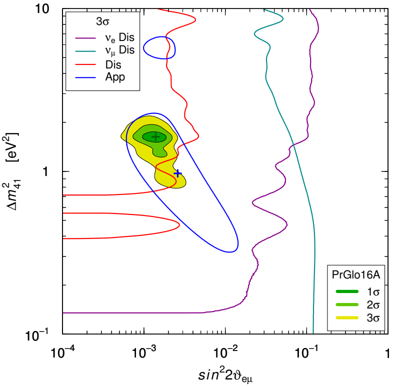
ν_μ DIS

$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$

$\nu_\mu \to \nu_e$ APP

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

[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]

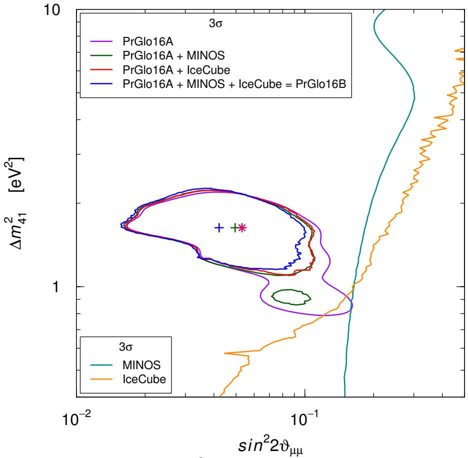


- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- PrGlo16A = 2016 data except MINOS and IceCube [Gariazzo, CG, Laveder, Li, JHEP 1706 (2017) 135]
- $\Delta\chi^2_{\text{NO}}/\text{NDF}_{\text{NO}} = 48.3/3 \Rightarrow \approx 6.4\sigma$ anom.
- Best Fit: $\Delta m^2_{41} = 1.6\,\text{eV}^2$

  $|U_{e4}|^2 = 0.026 \quad |U_{m4}|^2 = 0.013$
- $\chi^2_{\text{min}}/\text{NDF} = 262.0/244 \Rightarrow \text{GoF} = 20\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 3.8/2 \Rightarrow \text{GoF}_{\text{PG}} = 15\%$
- Similar tension in 3+2, 3+3, ..., 3+N_s

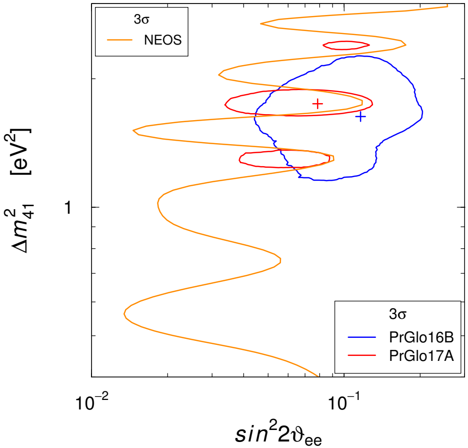
[CG, Zavanin, MPLA 31 (2015) 1650003]

Effects of MINOS and IceCube



- IceCube effect in agreement with
  Collin, Arguelles, Conrad, Shaevitz, PRL 117 (2016) 221801
- Best Fit: $\Delta m^2_{41} = 1.6\,\text{eV}^2 \quad |U_{e4}|^2 = 0.030 \quad |U_{\mu 4}|^2 = 0.011$
- $\chi^2_{\text{min}}/\text{NDF} = 530.3/519 \Rightarrow \text{GoF} = 36\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 4.7/2 \Rightarrow \text{GoF}_{\text{PG}} = 9.7\%$ ← More tension!

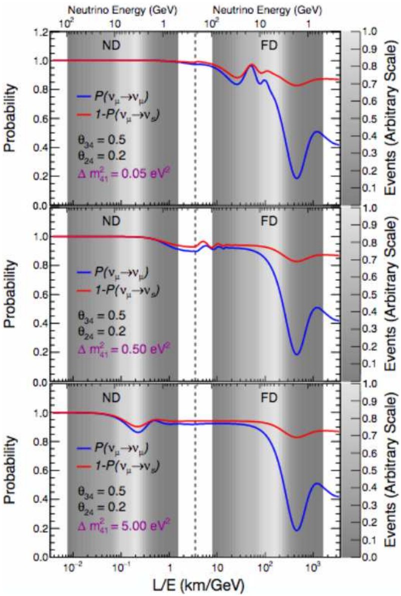
Effects of NEOS

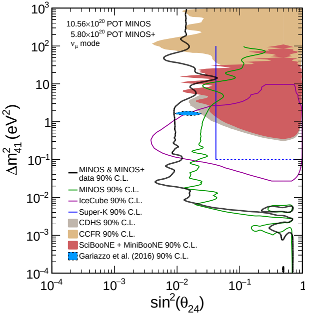


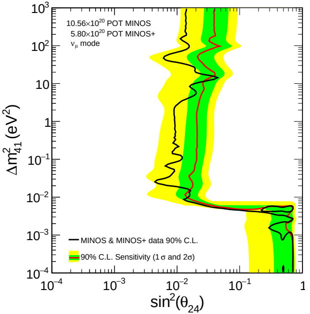
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$ $|U_{e4}|^2 = 0.020$ $|U_{\mu 4}|^2 = 0.015$
- $\chi^2_{\text{min}}/\text{NDF} = 595.1/579 \Rightarrow \text{GoF} = 31\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 7.2/2 \Rightarrow \text{GoF}_{\text{PG}} = 2.7\%$ $\leftarrow$ More tension!

New Bound from MINOS & MINOS+

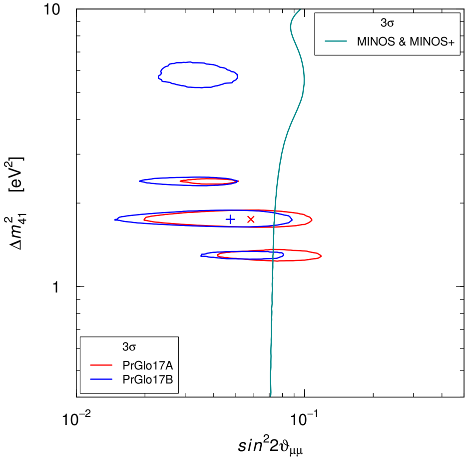
[arXiv:1710.06488]







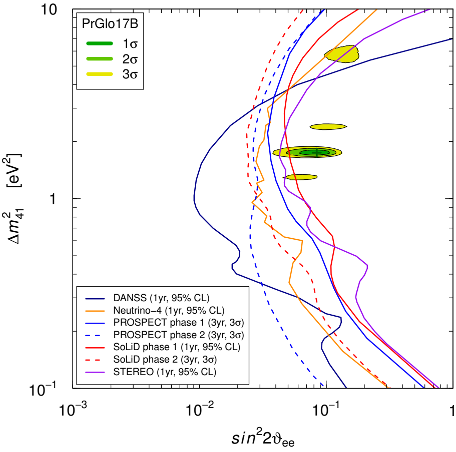
Effects of MINOS & MINOS+

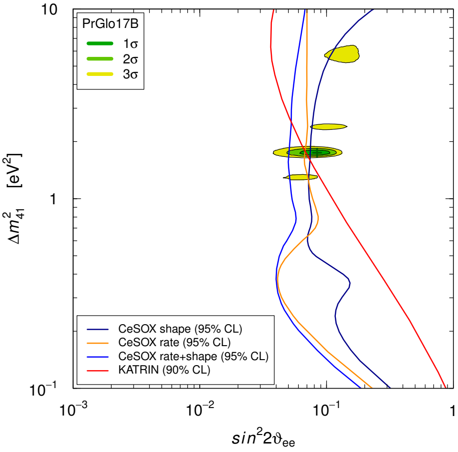


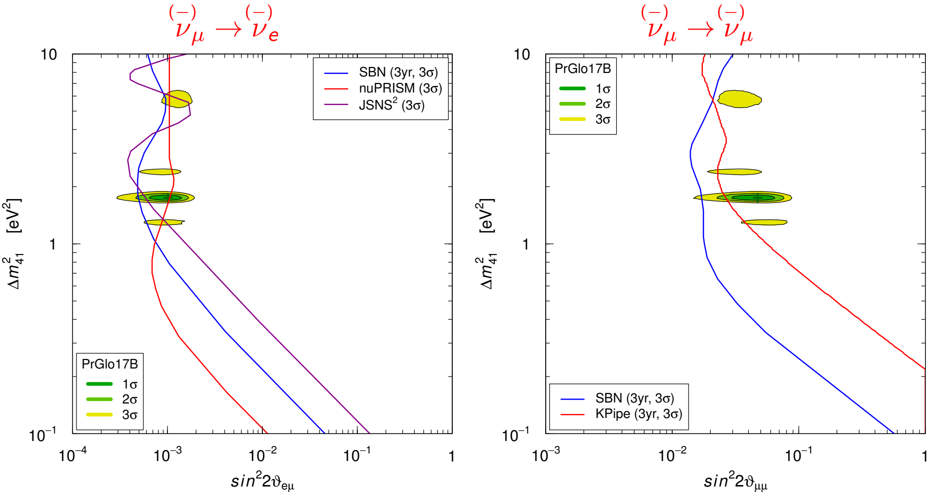
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$ $|U_{e4}|^2 = 0.021$ $|U_{\mu4}|^2 = 0.012$
- $\chi^2_{\text{min}}/\text{NDF} = 608.9/615 \Rightarrow \text{GoF} = 56\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 10.9/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.43\%$ $\leftarrow$ More tension!
- The MINOS & MINOS+ bound disfavors the LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal.

New Dedicated Experiments

$$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$$

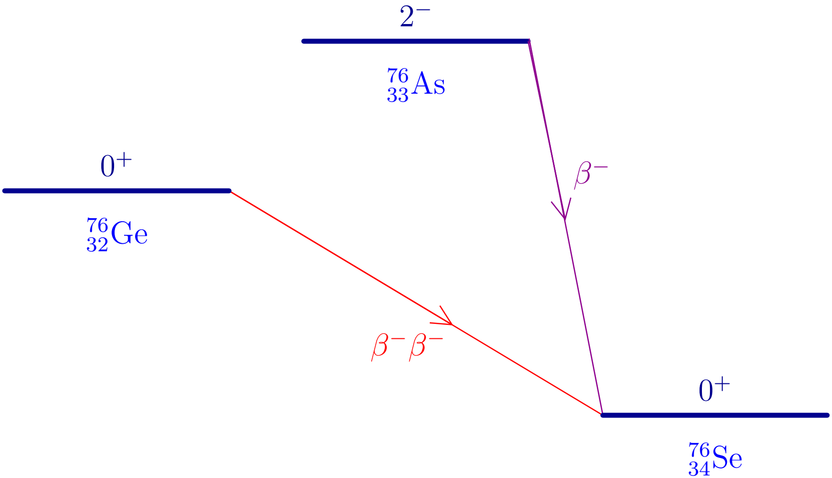






$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$
SBN (3yr, 3σ)
nuPRISM (3σ)
JSNS² (3σ)
PrGlo17B
1σ
2σ
3σ
Δm^2_{41} [eV²]
$sin^2 2\vartheta_{e\mu}$
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$
PrGlo17B
1σ
2σ
3σ
SBN (3yr, 3σ)
KPipe (3yr, 3σ)
Δm^2_{41} [eV²]
$sin^2 2\vartheta_{\mu\mu}$

Neutrinoless Double-Beta Decay



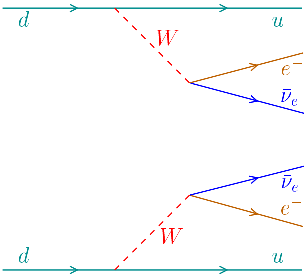
Effective Majorana Neutrino Mass: $m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$

Two-Neutrino Double-β Decay: $\Delta L = 0$

$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

$$(T^{2\nu}_{1/2})^{-1} = G_{2\nu}\,|\mathcal{M}_{2\nu}|^2$$

second order weak interaction process
in the Standard Model

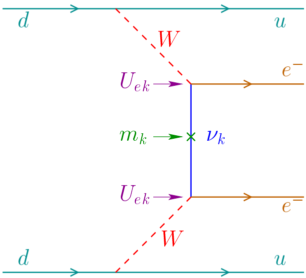


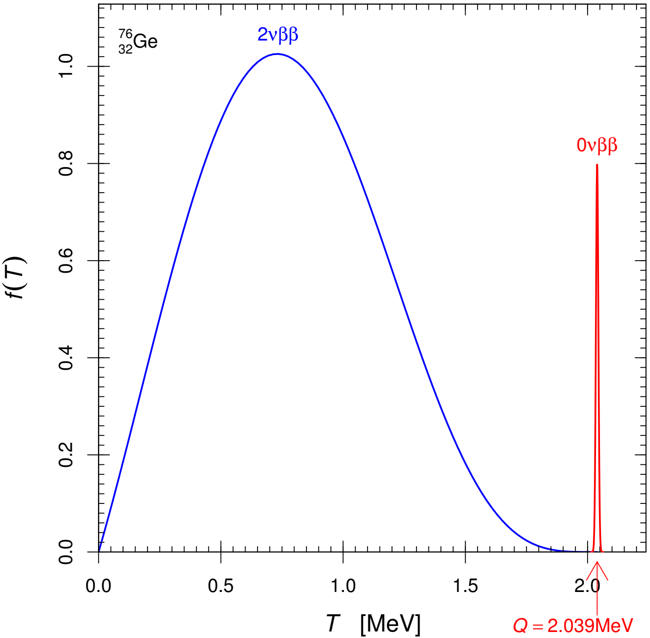
Neutrinoless Double-β Decay: $\Delta L = 2$

$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^-$$

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

effective Majorana mass $\qquad |m_{\beta\beta}| = \left|\sum_k U_{ek}^2\, m_k\right|$





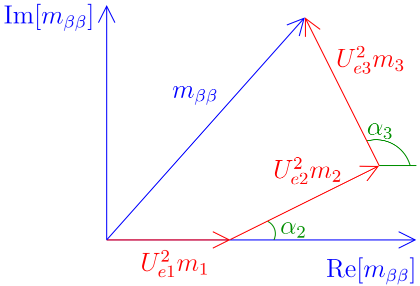
$^{76}_{32}$Ge
2νββ
0νββ
f(T)
T [MeV]
Q = 2.039MeV
0.0
0.5
1.0
1.5
2.0
0.2
0.4
0.6
0.8

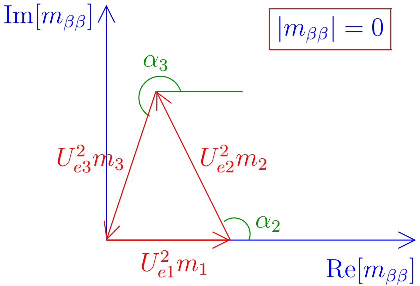
Effective Majorana Neutrino Mass

$$m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k \qquad \text{complex } U_{ek} \Rightarrow \text{possible cancellations}$$

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

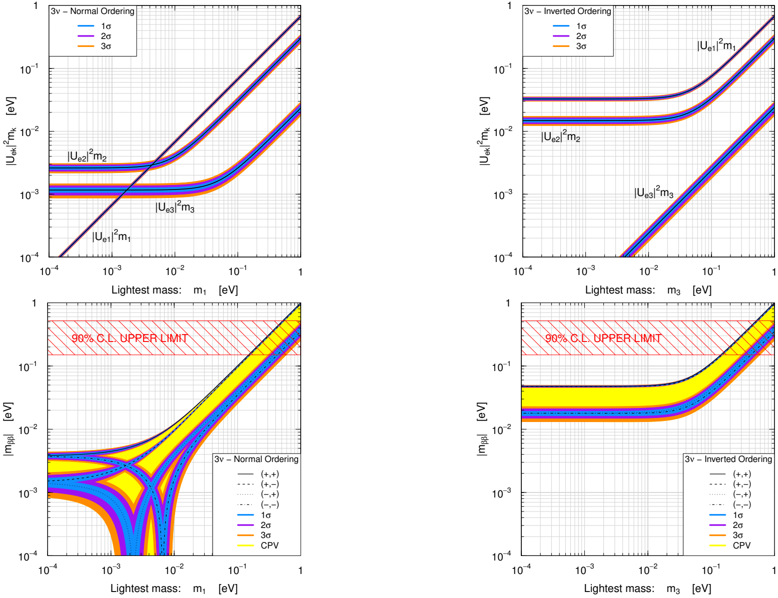
$$\alpha_2 = 2\lambda_2 \qquad \alpha_3 = 2\,(\lambda_3 - \delta_{13})$$





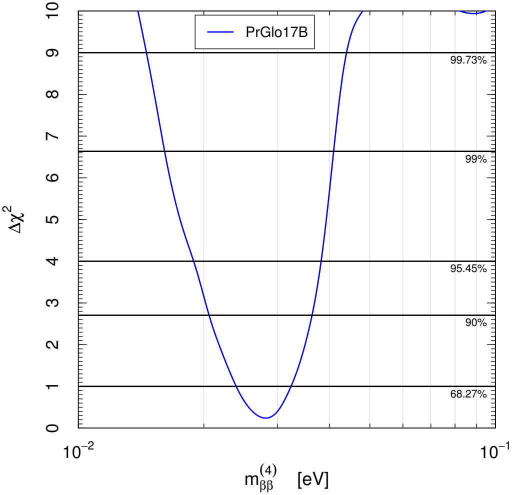
Predictions of 3ν-Mixing Paradigm

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



3+1 Mixing

$$m_{\beta\beta} = |U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, e^{i\alpha_{21}} \, m_2 + |U_{e3}|^2 \, e^{i\alpha_{31}} \, m_3 + |U_{e4}|^2 \, e^{i\alpha_{41}} \, m_4$$



$$m_{\beta\beta}^{(k)} = |U_{ek}|^2 m_k$$

$$m_1 \ll m_4$$

$$\Downarrow$$

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

warning:

possible cancellation with $m_{\beta\beta}^{(3\nu)}$

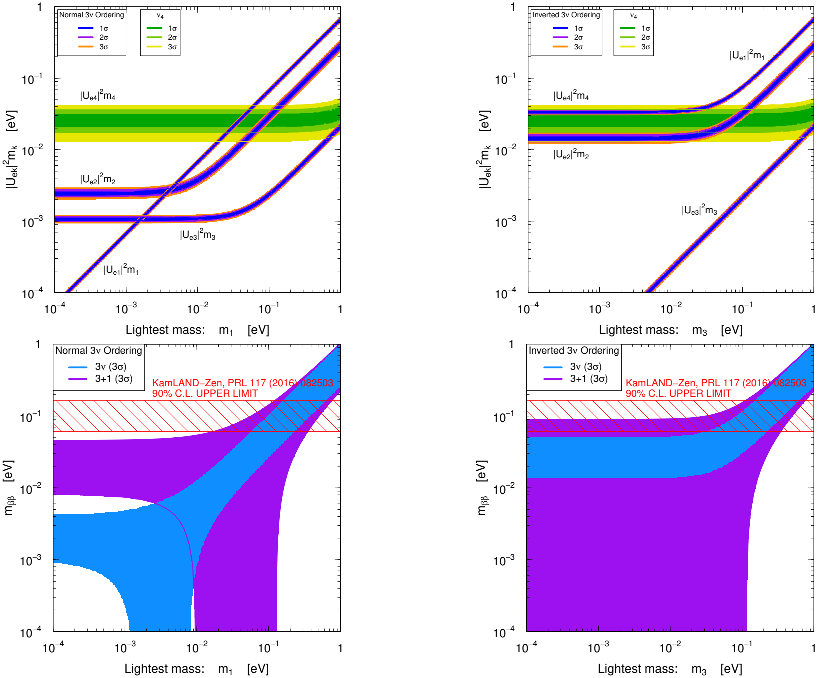
[Barry, Rodejohann, Zhang, JHEP 07 (2011) 091]

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

[Rodejohann, JPG 39 (2012) 124008]

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

[CG, Zavanin, JHEP 07 (2015) 171]

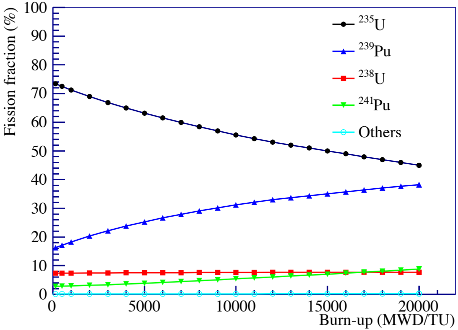

Normal 3ν Ordering
1σ
2σ
3σ
ν4
1σ
2σ
3σ
|Ue4|2m4
|Ue2|2m2
|Ue3|2m3
|Ue1|2m1
|Uek|2mk [eV]
Lightest mass: m1 [eV]
Inverted 3ν Ordering
1σ
2σ
3σ
ν4
1σ
2σ
3σ
|Ue1|2m1
|Ue4|2m4
|Ue2|2m2
|Ue3|2m3
|Uek|2mk [eV]
Lightest mass: m3 [eV]
Normal 3ν Ordering
3ν (3σ)
3+1 (3σ)
KamLAND−Zen, PRL 117 (2016) 082503
90% C.L. UPPER LIMIT
mββ [eV]
Lightest mass: m1 [eV]
Inverted 3ν Ordering
3ν (3σ)
3+1 (3σ)
KamLAND−Zen, PRL 117 (2016) 082503
90% C.L. UPPER LIMIT
mββ [eV]
Lightest mass: m3 [eV]

Daya Bay Reactor Fuel Evolution

[Daya Bay, PRL 118 (2017) 251801 (arXiv:1704.01082)]

- Reactor $\bar{\nu}_e$ flux produced by the β decays of the fission products of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu.
- Effective fission fractions:

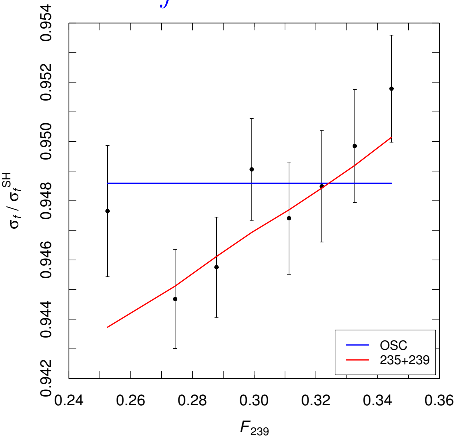
$$F_{235},\ F_{238},\ F_{239},\ F_{241}.$$

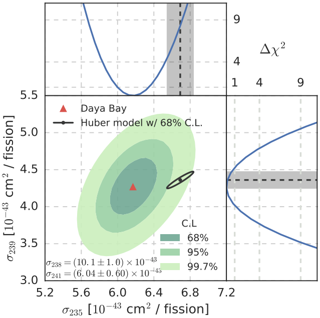


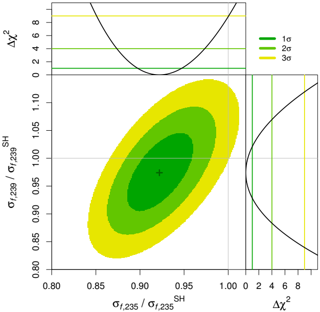
- Cross section per fission:

$$\sigma_f = \sum_{k=235,238,239,241} F_k\,\sigma_{f,k}$$

$$\sigma_{f,k} = \int dE_\nu\,\phi_k(E_\nu)\,\sigma(E_\nu)$$







- Best fit: mainly suppression of $\sigma_{f,235}$
- Equal fluxes suppression:

$$\Delta\chi^2/\mathrm{NDF} = 7.9/1$$

  disfavored at 2.8σ

- Equal fluxes suppression corresponds to SBL oscillations, but theoretical flux uncertainties must be taken into account

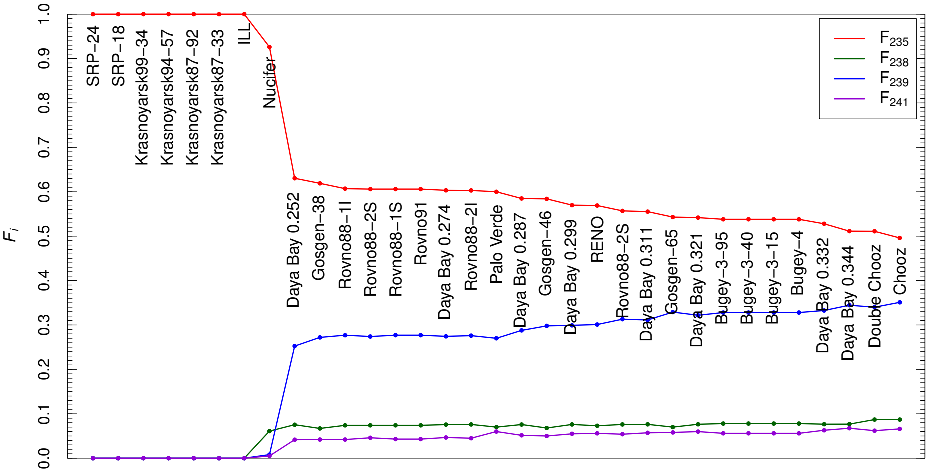
- With theoretical flux uncertainties:

Daya Bay	^{235}U	OSC
χ^2_{min}	3.8	9.5
NDF	7	7
GoF	80%	22%

- MC: OSC disfavored at 2.6σ

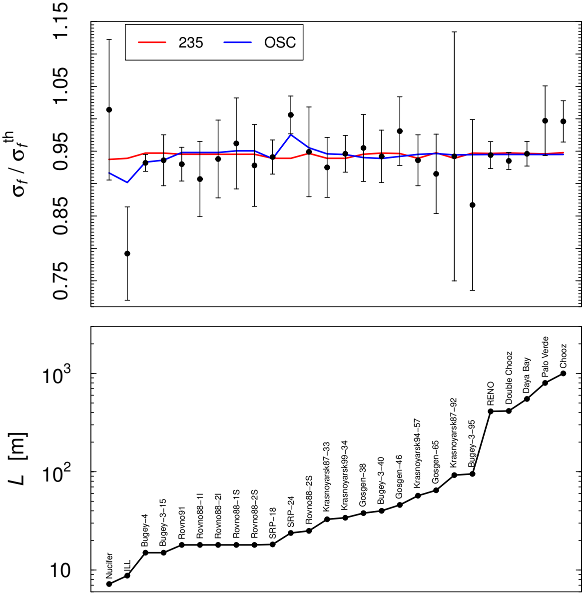
[CG, X.P. Ji, M. Laveder, Y.F. Li, B.R. Littlejohn, arXiv:1708.01133]

Fuel Fractions of All Reactor Experiments



All Reactors	^{235}U	OSC
χ^2_{min}	25.3	23.0
NDF	32	31
GoF	79%	85%

MC: ^{235}U disfavored at 1.7σ



Conclusions

- Exciting indications of sterile neutrinos (new physics!) at the eV scale:
  - LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal (caveat: single experimental signal).
  - Gallium ν_e disappearance (caveat: overestimated detector efficiency?).
  - Reactor $\bar{\nu}_e$ disappearance (caveat: flux calculation dependence).
- The MINOS & MINOS+ bound disfavors the LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal.
- Vigorous experimental program to check conclusively in a few years:
  - ν_e and $\bar{\nu}_e$ disappearance with reactors and radioactive sources.
  - $\nu_\mu \to \nu_e$ transitions with accelerator neutrinos.
  - ν_μ disappearance with accelerator neutrinos.
- Independent tests through effect of m_4 in β-decay and $\beta\beta_{0\nu}$-decay.
- Cosmology: strong tension with $\Delta N_{\text{eff}} = 1$ and $m_4 \approx 1\,\text{eV}$. It may be solved by a non-standard cosmological mechanism.
- Possibilities for the next years:
  - Reactor and source experiments ν_e and $\bar{\nu}_e$ observe SBL oscillations: big excitement and explosion of the field.
  - Otherwise: still marginal interest to check the LSND appearance signal.
  - In any case the possibility of the existence of sterile neutrinos related to New Physics beyond the Standard Model at different mass scales will continue to be studied (e.g keV sterile neutrinos).