Short-Baseline Neutrino Oscillation Anomalies and Light Sterile Neutrinos

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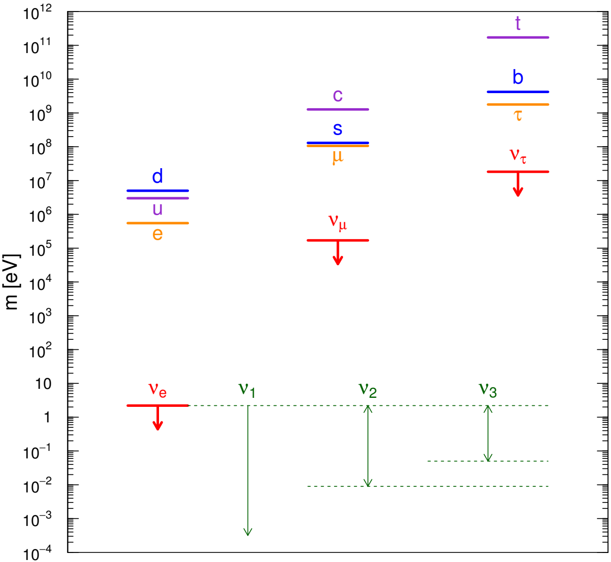
Fermion Mass Spectrum



Neutrino Mixing

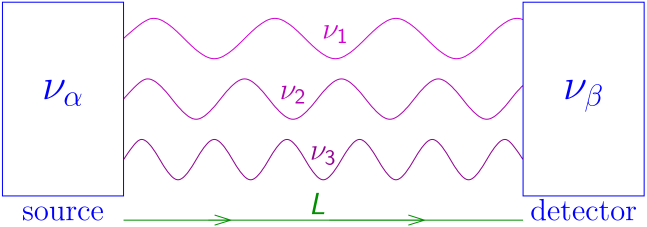
- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector
- Neutrino Mixing: a Flavor Neutrino is a superposition of Massive Neutrinos

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- U is the 3×3 unitary Neutrino Mixing Matrix

Neutrino Oscillations

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



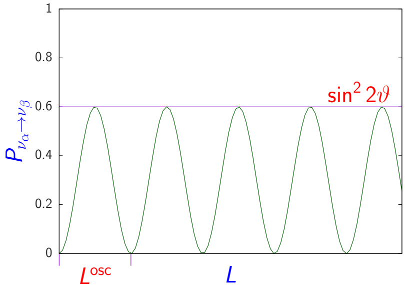
$$|\nu(t>0)\rangle = U_{\alpha 1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{\alpha 2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{\alpha 3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_\alpha\rangle$$

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

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

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

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



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)

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

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

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

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} $\Longleftrightarrow$ $|\Delta L| = 2$ 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)

$\rightarrow$

$$\begin{cases} \Delta m^2_{\mathrm{S}} = \Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\mathrm{eV}^2 \\ \sin^2\vartheta_{\mathrm{S}} = \sin^2\vartheta_{12} \simeq 0.30 \end{cases}$$

Three-Neutrino Mixing Ingredients

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

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)

$\rightarrow$

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

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

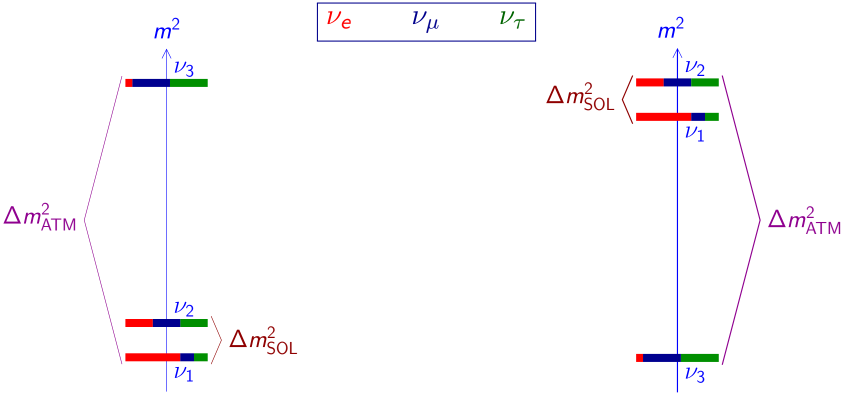
LBL Reactor (Daya Bay, RENO, Double Chooz)
$\bar{\nu}_e$ disappearance

$\rightarrow$

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

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

Mass Ordering



Normal Ordering

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

Inverted Ordering

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

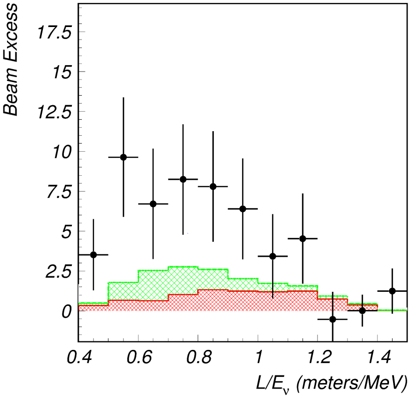
absolute scale is not determined by neutrino oscillation data

Short-Baseline Neutrino Oscillation Anomalies

LSND

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

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



- 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]

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

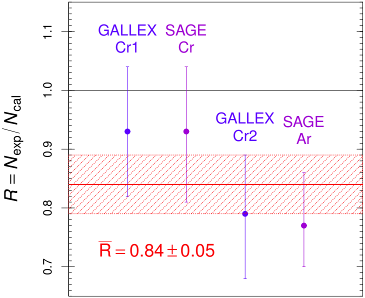
Gallium Anomaly

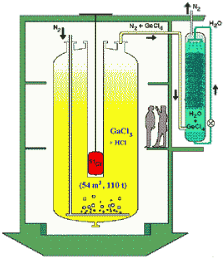
Gallium Radioactive Source Experiments: GALLEX and SAGE

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]

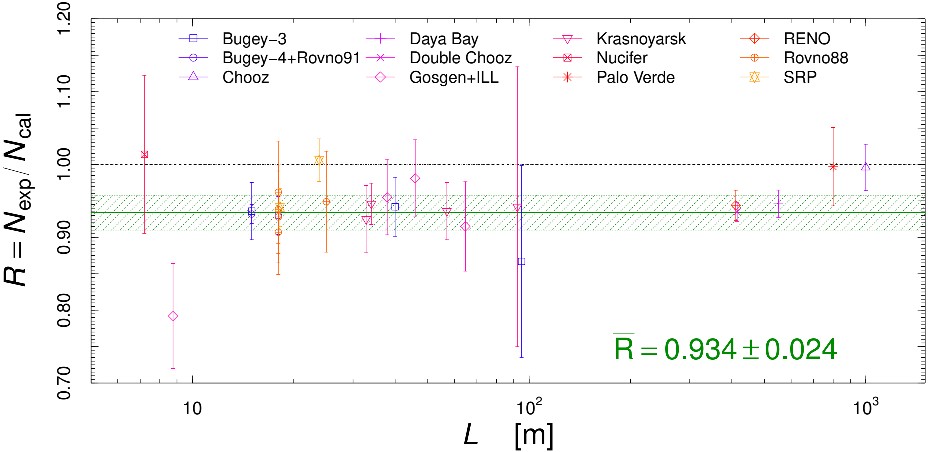
- ${}^{3}\text{He} + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + {}^{3}\text{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]

Reactor Electron Antineutrino Anomaly

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

New reactor $\bar{\nu}_e$ fluxes: Huber-Mueller (HM)

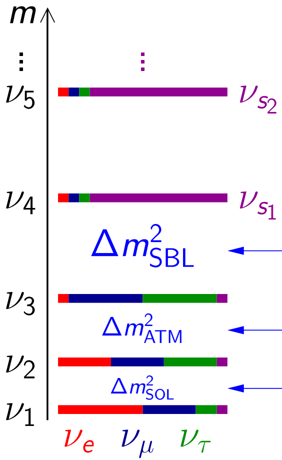
[Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



$\approx 2.8\sigma$ deficit

Beyond Three-Neutrino Mixing: Sterile Neutrinos

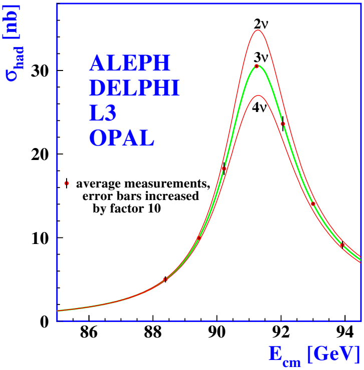
$$L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}$$



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

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

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



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

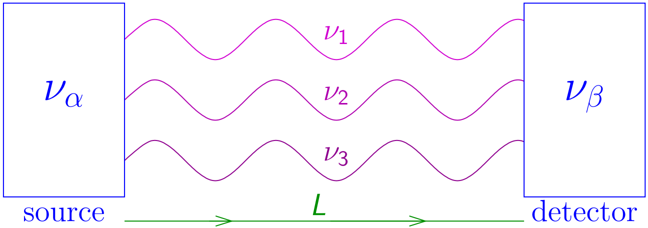
Terminology: a eV-scale sterile neutrino

means: a eV-scale massive neutrino which is mainly sterile

Short-Baseline Neutrino Oscillations

Three-Neutrino Mixing

$$|\nu_{\text{source}}\rangle = |\nu_\alpha\rangle = U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle$$



$$|\nu_{\text{detector}}\rangle \simeq U_{\alpha 1}\,e^{-iEL}\,|\nu_1\rangle + U_{\alpha 2}\,e^{-iEL}\,|\nu_2\rangle + U_{\alpha 3}\,e^{-iEL}\,|\nu_3\rangle = e^{-iEL}|\nu_\alpha\rangle$$

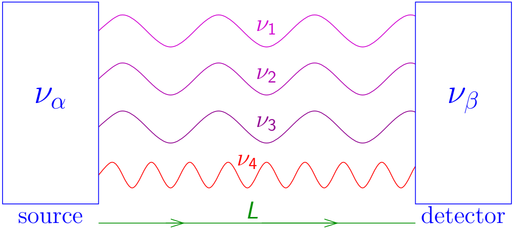
$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\beta | \nu_{\text{detector}} \rangle|^2 \simeq |e^{-iEL}\langle \nu_\beta | \nu_\alpha \rangle|^2 = \delta_{\alpha\beta}$$

No Observable Short-Baseline Neutrino Oscillations!

Short-Baseline Neutrino Oscillations

3+1 Neutrino Mixing

$$|\nu_{\text{source}}\rangle = |\nu_\alpha\rangle = U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle + U_{\alpha 4}\,|\nu_4\rangle$$



$$|\nu_{\text{detector}}\rangle \simeq e^{-iEL}\left(U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle\right) + U_{\alpha 4}\,e^{-iE_4 L}\,|\nu_3\rangle \neq |\nu_\alpha\rangle$$

$$P_{\nu_\alpha \to \nu_\beta}(L) = \left|\langle \nu_\beta | \nu_{\text{detector}}\rangle\right|^2 \neq \delta_{\alpha\beta}$$

Observable Short-Baseline Neutrino Oscillations!

The oscillation probabilities depend on U and

$$\Delta m^2_{\text{SBL}} = \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}$$

Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

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

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha4}|^2|U_{\beta4}|^2$$

Disappearance

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

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha4}|^2\left(1 - |U_{\alpha4}|^2\right)$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

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

- $\Delta m^2_{\text{SBL}} = \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}$
- 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]

3+1: Appearance vs Disappearance

- SBL Oscillation parameters: Δm^2_{41} $|U_{e4}|^2$ $|U_{\mu 4}|^2$ $(|U_{\tau 4}|^2)$
- Amplitude of ν_e disappearance:

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

- Amplitude of ν_μ disappearance:

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

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

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

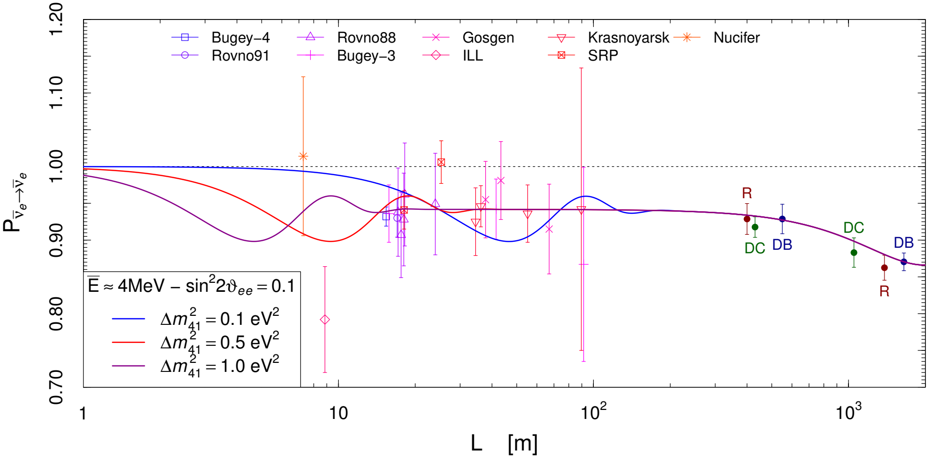
quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

$\Downarrow$

Appearance-Disappearance Tension

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

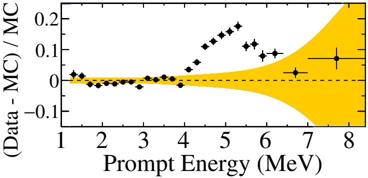
Reactor Electron Antineutrino Anomaly



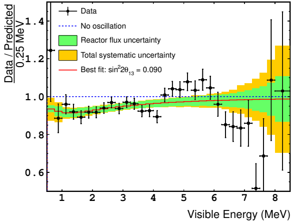
$$\Delta m^2_{SBL} \gtrsim 0.5\,eV^2 \gg \Delta m^2_{ATM}$$

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

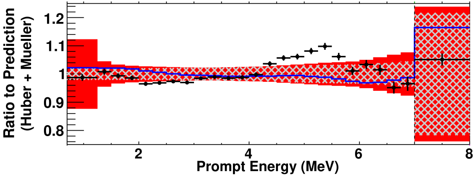
Reactor Antineutrino 5 MeV Bump



[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 RENO, DC, DB).
- It is likely due to a theoretical miscalculation of the spectrum.
- Heretic solution: detector energy nonlinearity. [Mention et al, PLB 773 (2017) 307]
- $\sim$ 3% effect on total flux, but if it is an excess it increases the anomaly!
- No post-bump complete calculation of the neutrino fluxes.
- Nominal Huber-Mueller flux calculation uncertainty: $\sim$ 2.7%.
- Post-bump estimate of the flux uncertainty due to unknown forbidden decays: $\sim$ 5%.

[Hayes and Vogel, ARNPS 66 (2016) 219]

Reactor Fuel Evolution

- Reactor $\bar{\nu}_e$ flux produced by the β decays of the fission products of

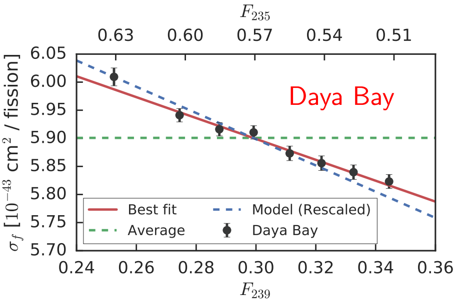
  $^{235}U \quad ^{238}U \quad ^{239}Pu \quad ^{241}Pu$

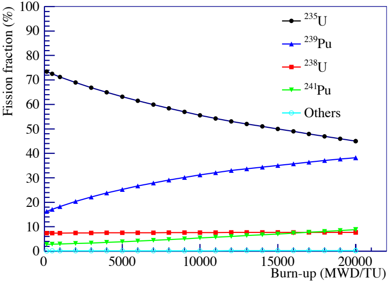
- Effective fission fractions:

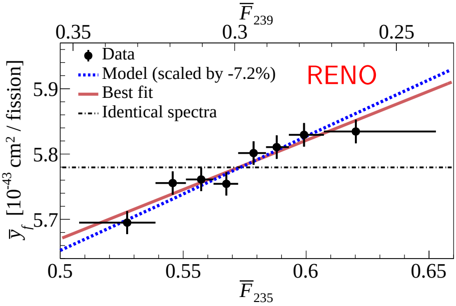
  $F_{235} \quad F_{238} \quad F_{239} \quad F_{241}$

- Cross section per fission:

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

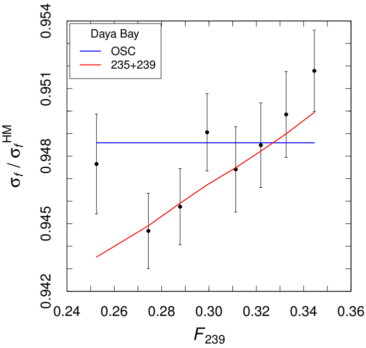






Daya Bay

[PRL 118 (2017) 251801 (arXiv:1704.01082)]



OSC: $P_{\bar{\nu}_e \to \bar{\nu}_e} = 0.942 \pm 0.030$

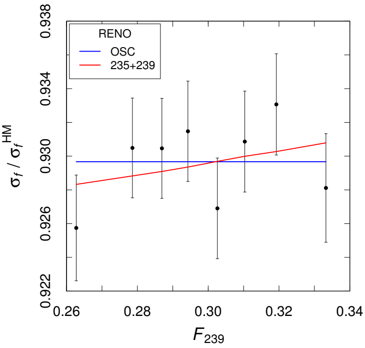
$\chi^2/\text{NDF} = 9.5/7 \quad \text{GoF} = 22\%$

235+239: $\begin{cases} r_{235} = 0.922 \pm 0.024 \\ r_{239} = 0.974 \pm 0.046 \end{cases}$

$\chi^2/\text{NDF} = 3.6/6 \quad \text{GoF} = 73\%$

RENO

[arXiv:1806.00574]



OSC: $P_{\bar{\nu}_e \to \bar{\nu}_e} = 0.928 \pm 0.026$

$\chi^2/\text{NDF} = 4.6/7 \quad \text{GoF} = 71\%$

235+239: $\begin{cases} r_{235} = 0.913 \pm 0.021 \\ r_{239} = 0.921 \pm 0.052 \end{cases}$

$\chi^2/\text{NDF} = 4.2/6 \quad \text{GoF} = 65\%$

- Daya Bay favors a suppression of the ^{235}U flux over oscillations.
- However, the addition of other reactor data favors oscillations or, better, ^{235}U and/or ^{239}U flux suppression plus oscillations.

[CG, Ji, Laveder, Li, Littlejohn, JHEP 1710 (2017)]

- RENO data are almost equally fitted by a suppression of the ^{235}U flux and oscillations.
- Even if there are short-baseline neutrino oscillations, it is likely that the reactor antineutrino flux calculations must be corrected (most likely the ^{235}U flux) to fit:
  1. The 5 MeV bump
  2. The fuel evolution data
- The search for short-baseline neutrino oscillations needs

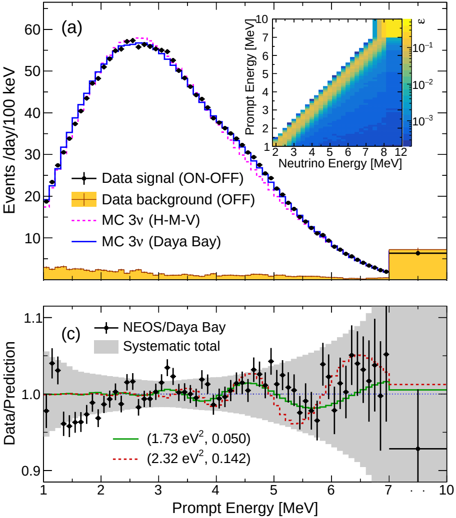
model-independent information

$\Uparrow$

ratios of spectra at different distances

NEOS

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

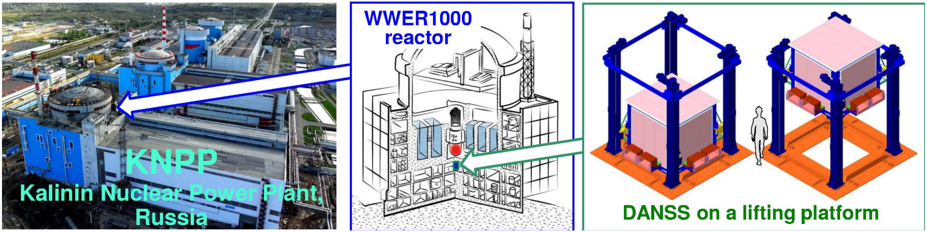


- Hanbit Nuclear Power Complex in Yeong-gwang, Korea.
- Thermal power of 2.8 GW.
- Detector: a ton of Gd-loaded liquid scintillator in a gallery approximately 24 m from the reactor core.
- The measured antineutrino event rate is 1976 per day with a signal to background ratio of about 22.

DANSS

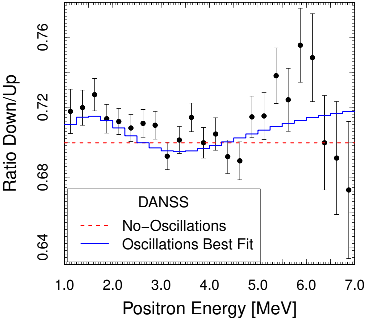
[Solvay Workshop, 1 December 2017; La Thuile 2018, 3 March 2018; Neutrino 2018, 8 June 2018]

Detector of reactor AntiNeutrino based on Solid Scintillator



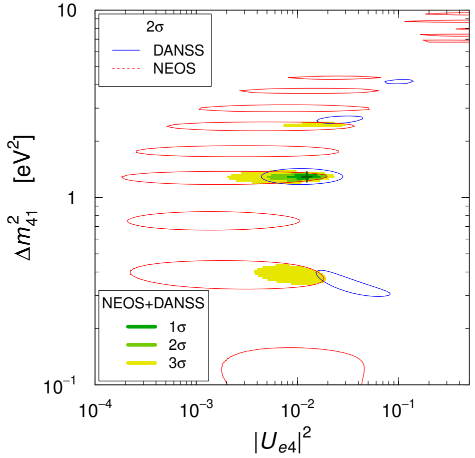
- Installed on a movable platform under a 3 GW reactor.
- Large neutrino flux.
- Reactor shielding of cosmic rays.
- Variable source-detector distance with the same detector!

$$\text{Down} = 12.7\,\text{m}$$
$$\text{Up} = 10.7\,\text{m}$$



Model-Independent $\bar{\nu}_e$ SBL Oscillations

[Gariazzo, CG, Laveder, Li, PLB 782 (2018) 13, arXiv:1801.06467]



$\sim 3.7\sigma$

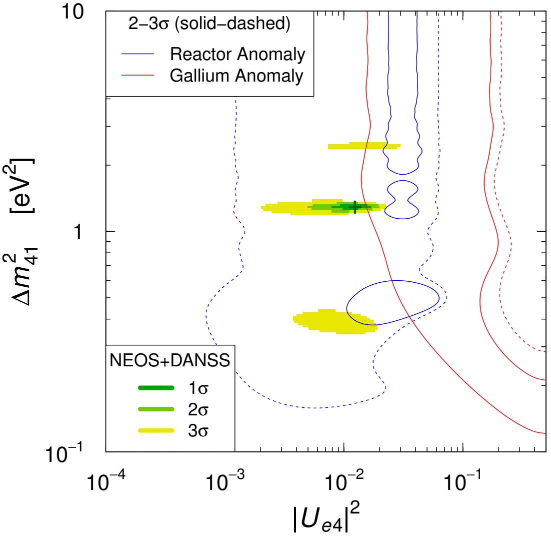
$\Delta m^2_{41} = 1.29 \pm 0.03$

$|U_{e4}|^2 = 0.012 \pm 0.003$

$|U_{e3}|^2 = 0.022 \pm 0.001$

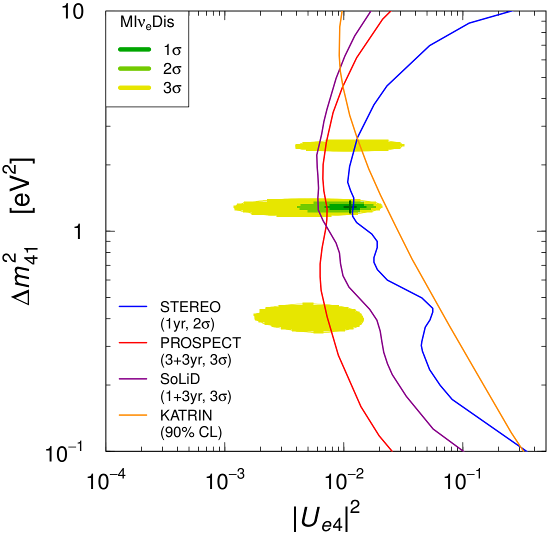
[See also Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

Comparison with the Reactor and Gallium Anomalies



- 3σ agreement.
- 2σ tension.
- Small overestimate of the reactor fluxes.
- Small overestimate of the GALLEX and SAGE efficiencies.

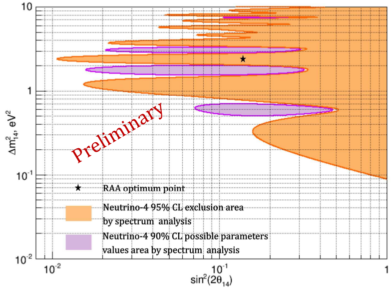
Global Model-Independent ν_e and $\bar{\nu}_e$ Disappearance



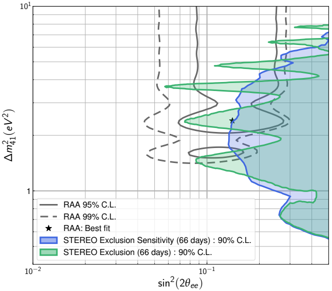
- NEOS and DANSS.
- Reactor rates with free ^{235}U and ^{239}Pu fluxes: r_{235} and r_{239}.
- Gallium data with free GALLEX and SAGE efficiencies: η_G and η_S.
- New reactor experiments: STEREO, Neutrino-4, SoLiD, PROSPECT
- Kinematic ν_4 mass measurement: KATRIN

[See also Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

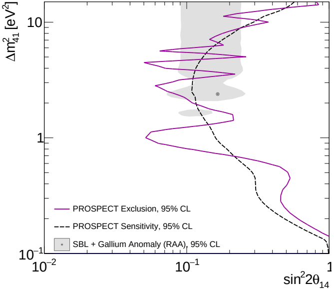
Neutrino-4 [PPNS 2018]



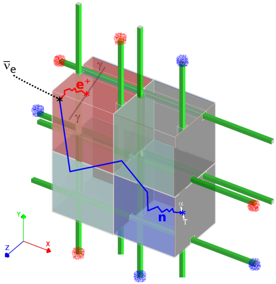
STEREO [arXiv:1806.02096 and Neutrino 2018]

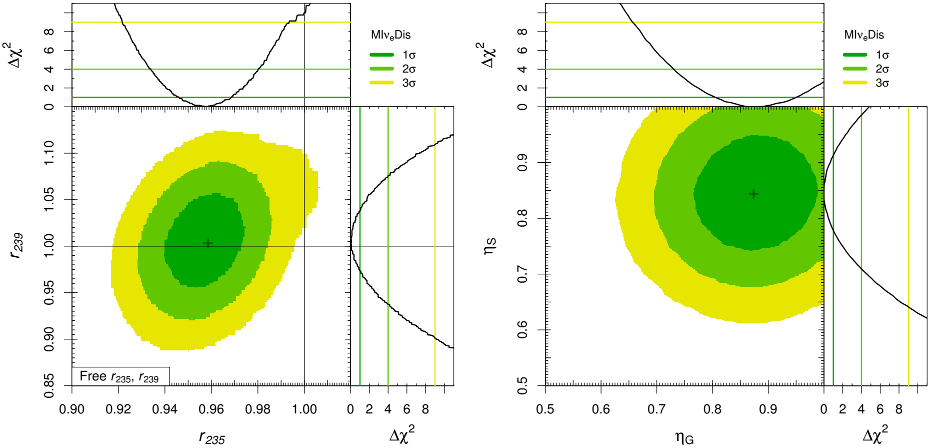


PROSPECT [arXiv:1806.02784 and Neutrino 2018]



SoLiD [arXiv:1806.02461 and Neutrino 2018]



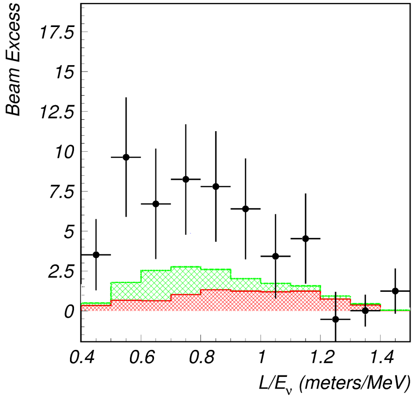


- Indication of $r_{235} < 1$.
- Likely small overestimate of the GALLEX and SAGE efficiencies.

LSND

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

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



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

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

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

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

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

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

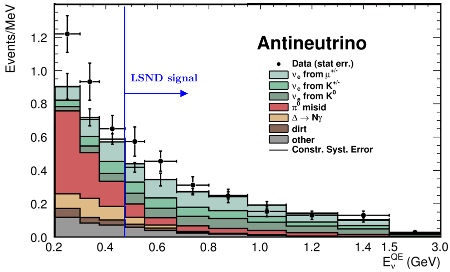
Well-known detection process of $\bar{\nu}_e$

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

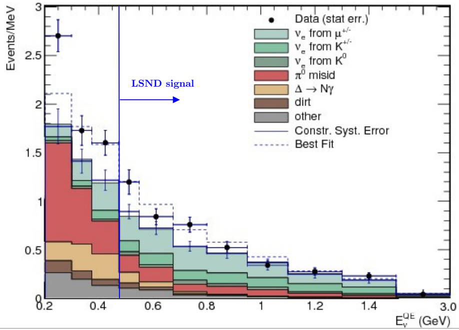
[PRD 65 (2002) 112001]

MiniBooNE

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



$\nu_\mu \to \nu_e$ [arXiv:1805.12028]



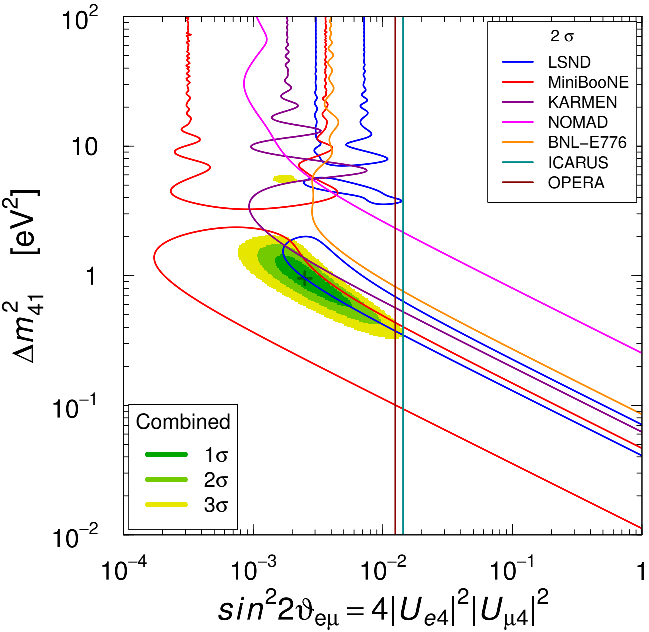
- Purpose: check the LSND signal
- Different $L \simeq 541\,\text{m}$
- Different $200\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$
- Similar $L/E \iff$ oscillations
- No money, no Near Detector
- Agreement with LSND for

  $$E \gtrsim 475\,\text{MeV}$$

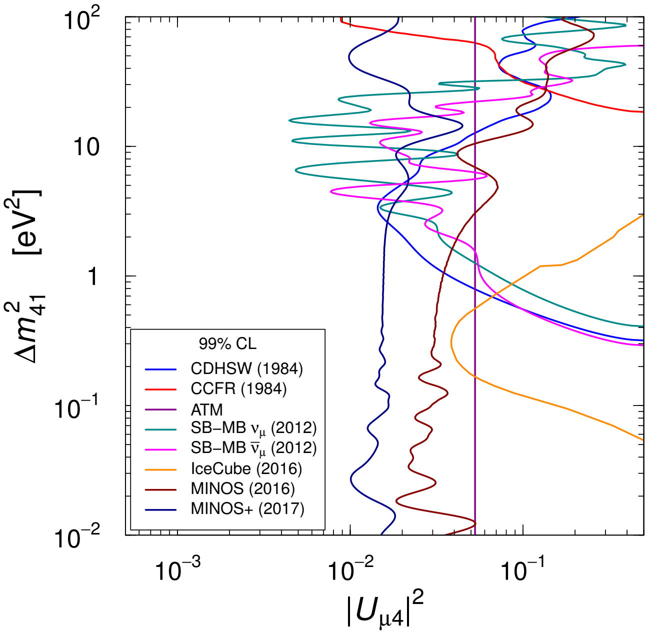
- Low-energy anomaly to be checked by MicroBooNE
- Pragmatic Approach:

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

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



ν_μ and $\bar{\nu}_\mu$ Disappearance

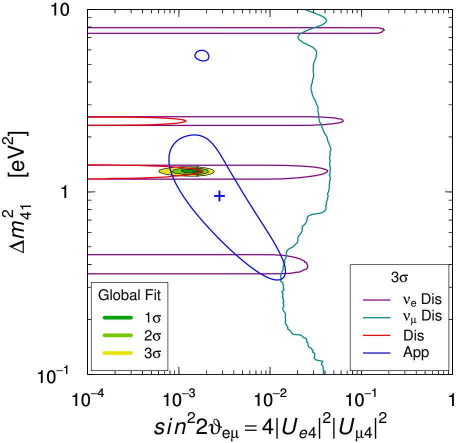


3+1 Appearance-Disappearance Tension

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



- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- Global Fit without MINOS+
  $\chi^2_{PG}/NDF_{PG} = 7.8/2 \Rightarrow GoF_{PG} = 2\%$
- Similar tension in
  $3+2, \quad 3+3, \quad \ldots, \quad 3+N_s$

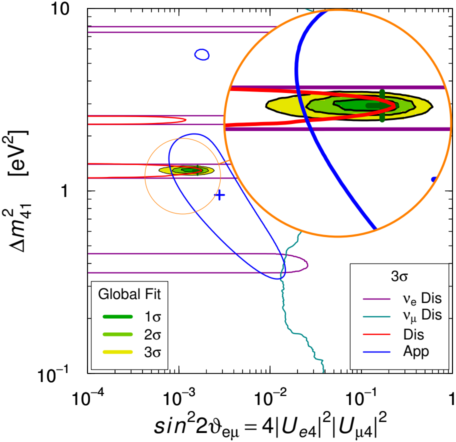
[CG, Zavanin, MPLA 31 (2015) 1650003]

3+1 Appearance-Disappearance Tension

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

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

$\nu_\mu \to \nu_e$ APP
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$



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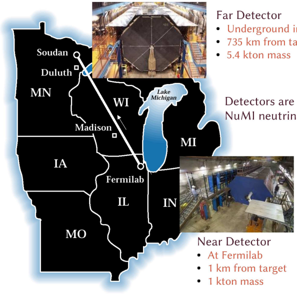
[CG, Zavanin, MPLA 31 (2015) 1650003]

New Bound from MINOS+

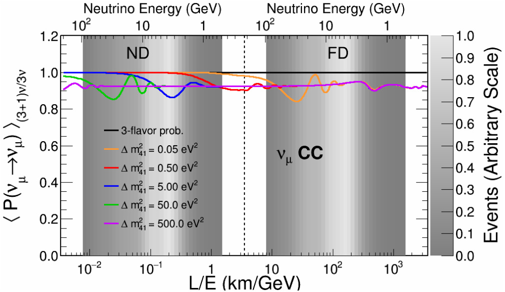


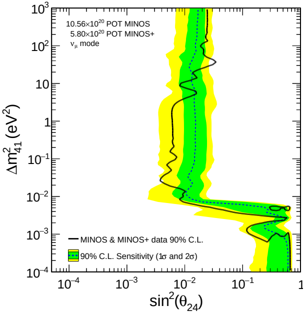
Far Detector
- Underground in Soudan mine
- 735 km from target
- 5.4 kton mass

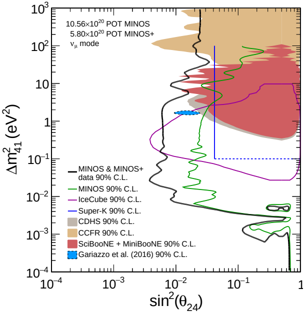
Detectors are on-axis for NuMI neutrino beam

Near Detector
- At Fermilab
- 1 km from target
- 1 kton mass

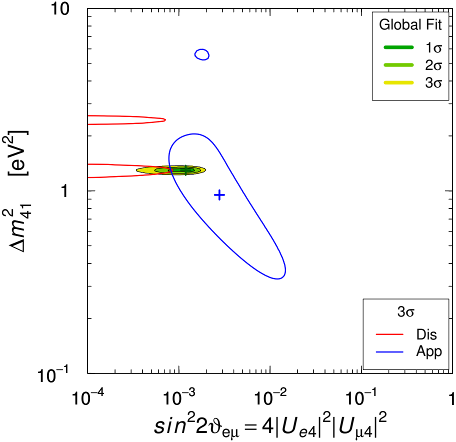
[arXiv:1710.06488]

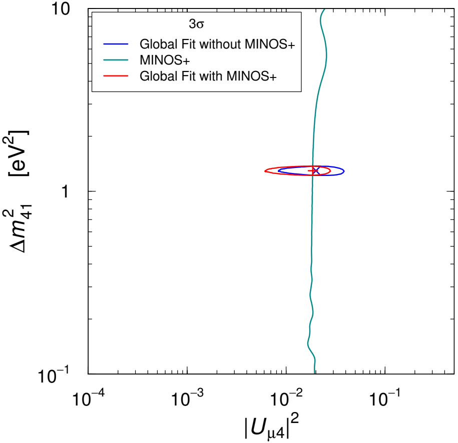






Effects of MINOS+





- $\chi^2_{PG}/NDF_{PG} = 18.3/2 \Rightarrow GoF_{PG} = 0.01\%$ $\longleftarrow$ Intolerable tension!
- The MINOS+ bound (if correct) disfavors the LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal.

[See also Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

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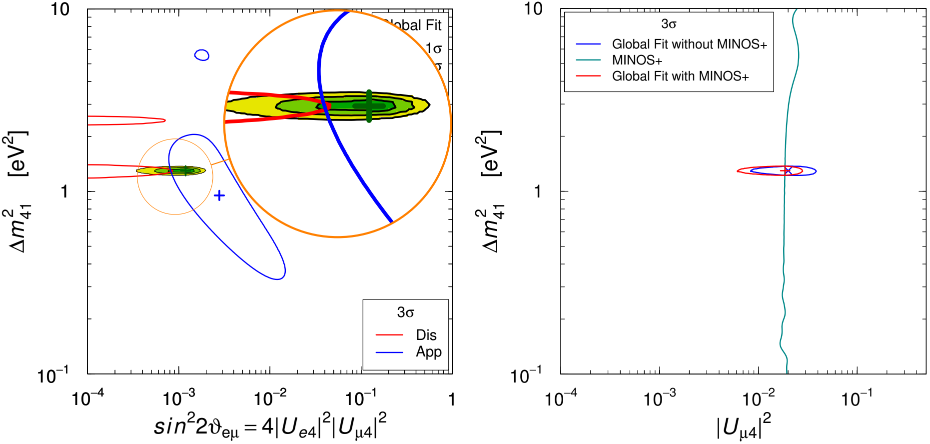

- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 18.3/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.01\%$ $\leftarrow$ Intolerable tension!
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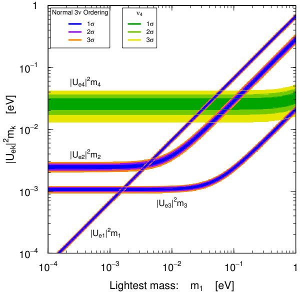
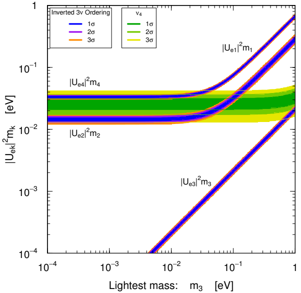
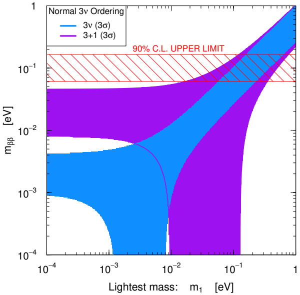
[See also Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

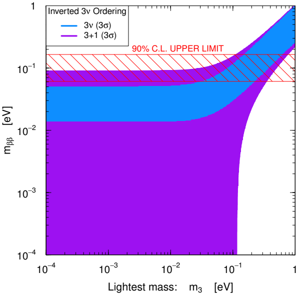
Neutrinoless Double-Beta Decay

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









Conclusions

- Exciting model-independent indication of light sterile neutrinos at the eV scale from the NEOS and DANSS experiments $\Longrightarrow$ New Physics beyond the Standard Model!
- Agreement with the Reactor and Gallium Anomalies $\Longrightarrow$ Needed revision of the ^{235}U calculation and small decrease of the GALLEX and SAGE efficiencies.
- Can be checked in the near future by the reactor experiments STEREO, Neutrino-4, SoLid, PROSPECT.
- Independent tests through effect of m_4 in β-decay (KATRIN), EC (ECHo, HOLMES) and $\beta\beta_{0\nu}$-decay.
- The MINOS+ bound (if correct) disfavors the LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal.