

Status of eV Sterile Neutrinos

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Neutrino Oscillations

$$\nu_{\alpha L} = \sum_k U_{\alpha k} \nu_{kL}$$

$$\alpha = e, \mu, \tau$$

$$P_{\nu_{\alpha} \rightarrow \nu_{\beta}}(L, E) = \underbrace{\delta_{\alpha\beta} - 4 \sum_{k>j} \text{Re}[U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*]}_{\text{CP conserving}} \sin^2 \left(\frac{\Delta m_{kj}^2 L}{4E} \right) + \underbrace{2 \sum_{k>j} \text{Im}[U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*]}_{\text{CP violating}} \sin \left(\frac{\Delta m_{kj}^2 L}{2E} \right)$$

- ▶ Squared-mass differences: $\Delta m_{kj}^2 = m_k^2 - m_j^2$
- ▶ Mixing: $U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*$ quartic rephasing invariants
- ▶ Jarlskog invariant: $J_{\text{CP}} = \text{Im}[U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*]$

Three-Neutrino Mixing Paradigm

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

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

$\left(\begin{array}{l} \text{SNO, BOREXino} \\ \text{Super-Kamiokande} \\ \text{GALLEX/GNO, SAGE} \\ \text{Homestake, Kamiokande} \\ \text{(KamLAND)} \end{array} \right)$

$\rightarrow \left\{ \begin{array}{l} \Delta m_S^2 = \Delta m_{21}^2 \simeq 7.4 \times 10^{-5} \text{ eV}^2 \\ \sin^2 \vartheta_S = \sin^2 \vartheta_{12} \simeq 0.30 \end{array} \right.$

Atmospheric
 $\nu_\mu \rightarrow \nu_\tau$

LBL Accelerator
 ν_μ disappearance

LBL Accelerator
 $\nu_\mu \rightarrow \nu_\tau$

$\left(\begin{array}{l} \text{Super-Kamiokande} \\ \text{Kamiokande, IMB} \\ \text{MACRO, Soudan-2} \\ \text{(K2K, MINOS)} \\ \text{T2K, NO}\nu\text{A} \\ \text{(Opera)} \end{array} \right)$

$\rightarrow \left\{ \begin{array}{l} \Delta m_A^2 = |\Delta m_{31}^2| \simeq 2.5 \times 10^{-3} \text{ eV}^2 \\ \sin^2 \vartheta_A = \sin^2 \vartheta_{23} \simeq 0.50 \end{array} \right.$

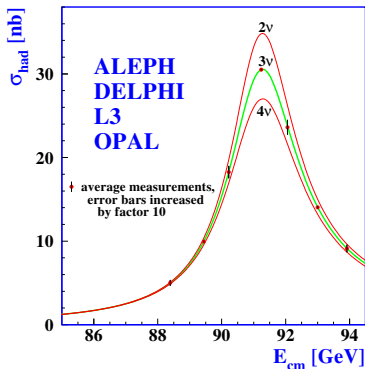
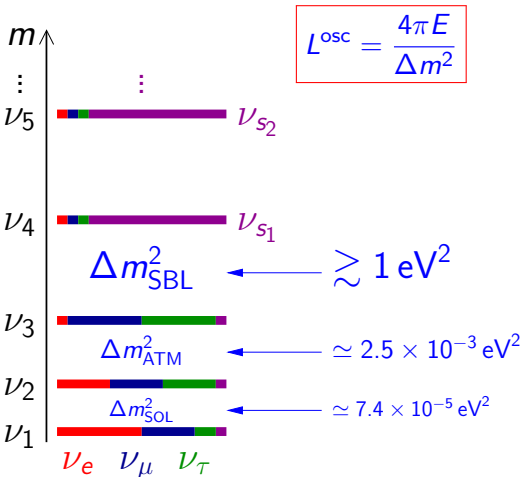
LBL Accelerator
 $\nu_\mu \rightarrow \nu_e$

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

$\left(\begin{array}{l} \text{(T2K, MINOS, NO}\nu\text{A)} \\ \text{(Daya Bay, RENO)} \\ \text{Double Chooz} \end{array} \right)$

$\rightarrow \left\{ \begin{array}{l} \Delta m_A^2 = |\Delta m_{31}^2| \\ \sin^2 \vartheta_{13} \simeq 0.022 \end{array} \right.$

Beyond Three-Neutrino Mixing: Sterile Neutrinos



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

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

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**

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

- ▶ Sterile means **no standard model interactions**

[Pontecorvo, Sov. Phys. JETP 26 (1968) 984]

- ▶ Active neutrinos (ν_e, ν_μ, ν_τ) can oscillate into light sterile neutrinos (ν_s)
- ▶ Observables:
 - ▶ **Disappearance** of active neutrinos (**neutral current deficit**) \leftarrow CE ν NS
 - ▶ Indirect evidence through **combined fit of data** (**current indication**)
- ▶ Short-baseline anomalies + 3ν -mixing:

$$\begin{array}{cccccc} \Delta m_{21}^2 & \ll & |\Delta m_{31}^2| & \ll & |\Delta m_{41}^2| & \leq \dots \\ \nu_1 & & \nu_2 & & \nu_3 & & \nu_4 & & \dots \\ \nu_e & & \nu_\mu & & \nu_\tau & & \nu_{s1} & & \dots \end{array}$$

Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

$$P_{\nu_\alpha \rightarrow \nu_\beta}^{\text{SBL}(-)} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

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

Disappearance

$$P_{\nu_\alpha \rightarrow \nu_\alpha}^{\text{SBL}(-)} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

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

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

SBL

▶ CP violation is not observable in SBL experiments!

▶ Observable in LBL accelerator exp. sensitive to Δm_{ATM}^2 [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_{SOL}^2 [Long, Li, CG, PRD 87, 113004 (2013) 113004]

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

3+1: Appearance vs Disappearance

- ▶ Amplitude of ν_e disappearance:

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

- ▶ Amplitude of ν_μ disappearance:

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

- ▶ Amplitude of $\nu_\mu \rightarrow \nu_e$ transitions:

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

quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu4}|^2$



Appearance-Disappearance Tension

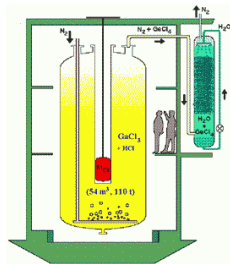
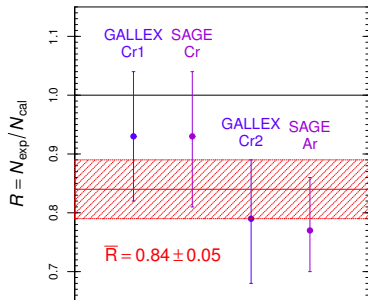
[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]

Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE



Test of Solar ν_e Detection:



$\approx 2.9\sigma$ deficit

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

$$\Delta m_{\text{SBL}}^2 \gtrsim 1 \text{ eV}^2 \gg \Delta m_{\text{ATM}}^2$$

[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]

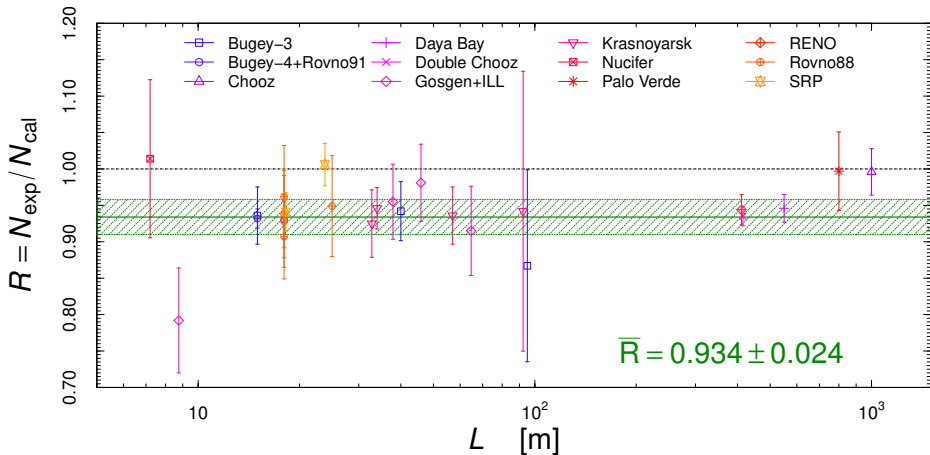
▶ ${}^3\text{He} + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + {}^3\text{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]

Reactor Electron Antineutrino Anomaly

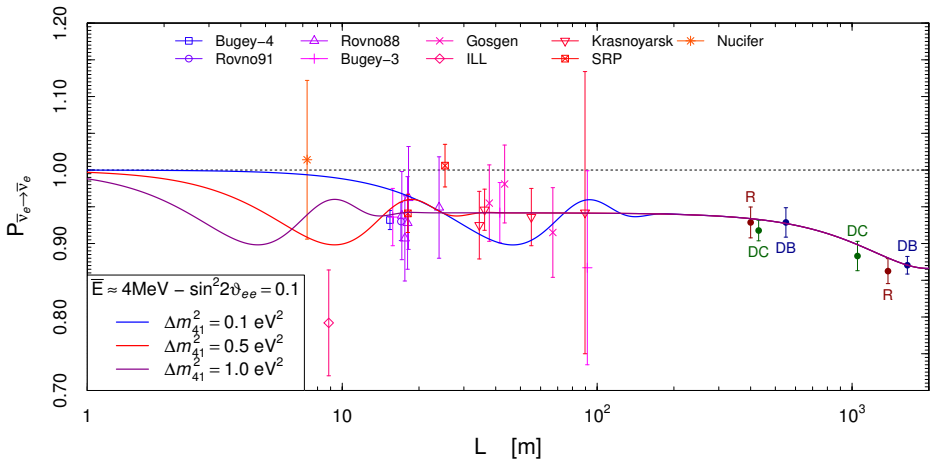
[Mention et al, PRD 83 (2011) 073006]

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

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



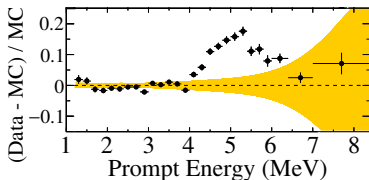
$\approx 2.8\sigma$ deficit



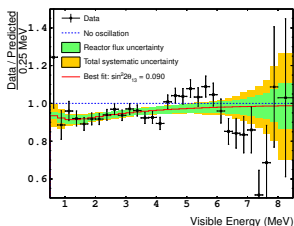
$$\Delta m_{\text{SBL}}^2 \gtrsim 0.5 \text{ eV}^2 \gg \Delta m_{\text{ATM}}^2$$

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

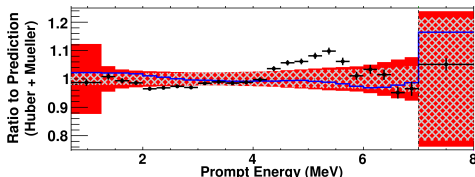
Reactor Antineutrino 5 MeV Bump



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]

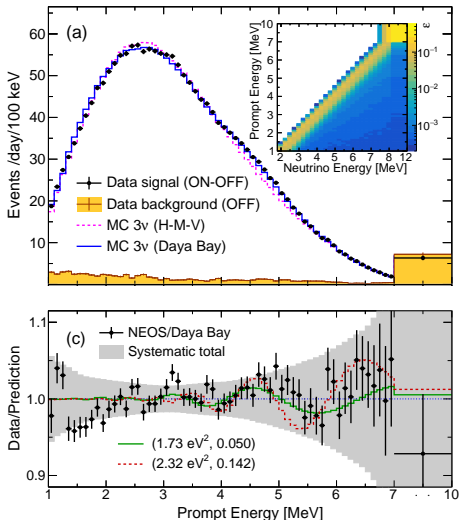


[Daya Bay, arXiv:1508.04233]

- ▶ 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. (Or to 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 Saclay-Huber flux calculation uncertainty: $\sim 2.5\%$.
- ▶ Increasing the flux uncertainty is a game that one can play, but there are only guesses, e.g. $\sim 5\%$ [Hayes and Vogel, ARNPS 66 (2016) 219].
- ▶ Bottom line: the status of the reactor anomaly is controversial.

NEOS

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

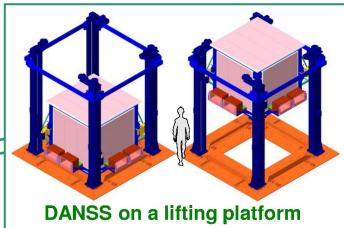
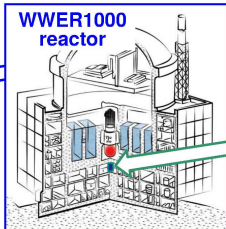


- ▶ Hanbit Nuclear Power Complex in Yeong-gwang, Korea.
- ▶ Thermal power of 2.8 GW.
- ▶ Detector: a ton of Gd-loaded liquid scintillator in a gallery approximately 24 m from the reactor core.
- ▶ The measured antineutrino event rate is 1976 per day with a signal to background ratio of about 22.

DANSS

[Danilov @ Solvay Workshop, 1 December 2017, and La Thuile 2018, 3 March 2018]

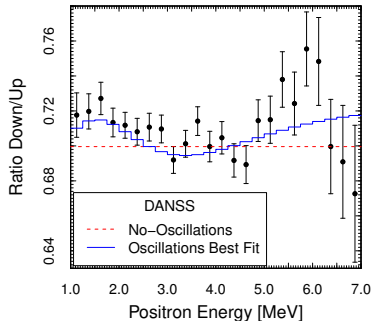
Detector of reactor AntiNeutrino based on Solid Scintillator



- ▶ 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!

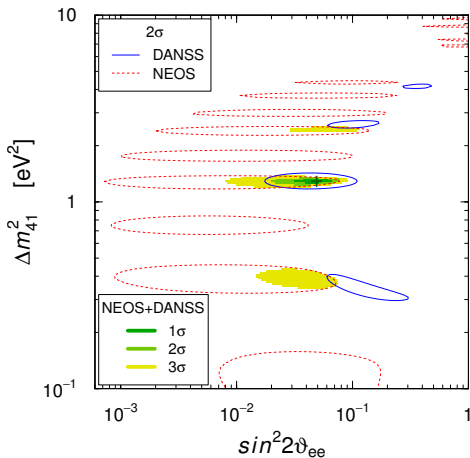
Down = 12.7 m

Up = 10.7 m



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

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



$$\sim 3.7\sigma$$

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

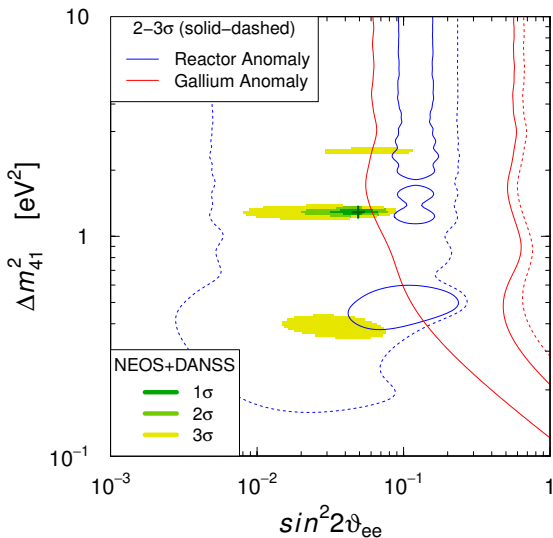
$$\sin^2 2\vartheta_{ee} = 0.049 \pm 0.011$$

$$\sin^2 \vartheta_{14} = |U_{e4}|^2$$

$$\sin^2 \vartheta_{14} = 0.012 \pm 0.003$$

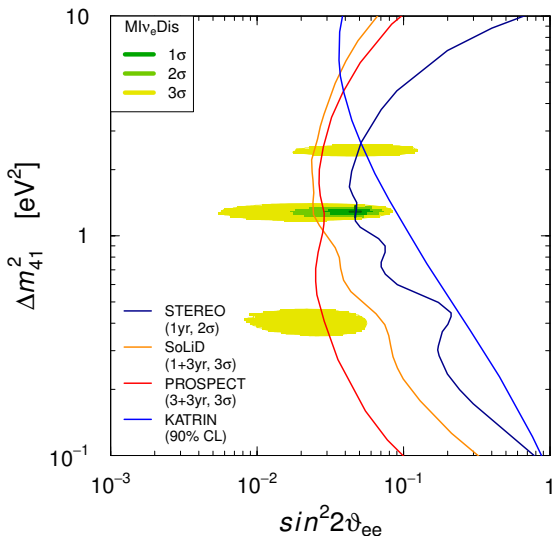
$$\sin^2 \vartheta_{13} = 0.022 \pm 0.001$$

Comparison with the Reactor and Gallium Anomalies



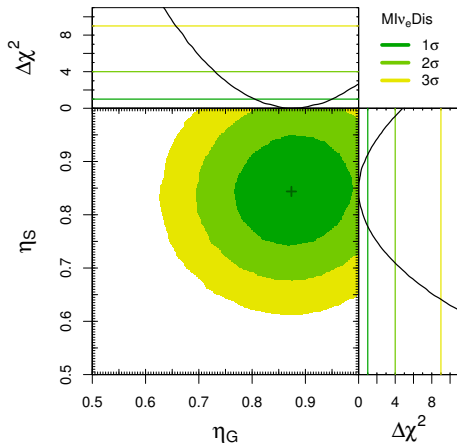
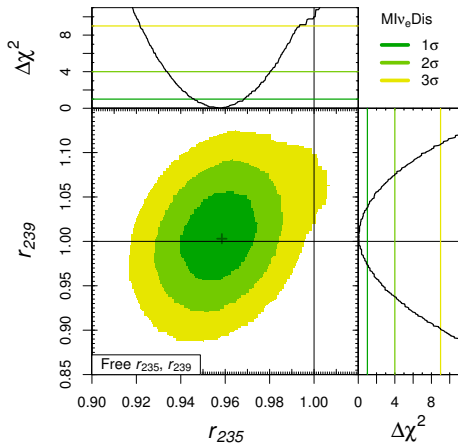
- ▶ 3 σ agreement.
- ▶ 2 σ tension.
- ▶ Small overestimate of the reactor fluxes.
- ▶ Small overestimate of the GALLEX and SAGE efficiencies.

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
- ▶ Kinematical ν_4 mass measurement: KATRIN

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



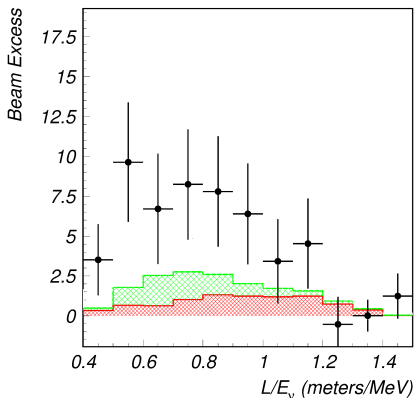
- ▶ Indication of $r_{235} < 1$.
- ▶ Likely small overestimate of the GALLEX and SAGE efficiencies.

LSND

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

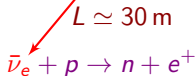
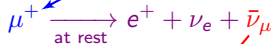
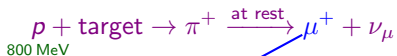
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$20 \text{ MeV} \leq E \leq 52.8 \text{ MeV}$$



$$\Delta m_{\text{SBL}}^2 \gtrsim 0.1 \text{ eV}^2 \gg \Delta m_{\text{ATM}}^2$$

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



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

$L \simeq 541 \text{ m}$

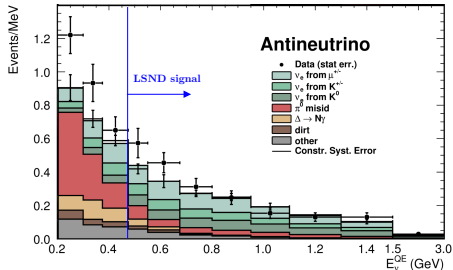
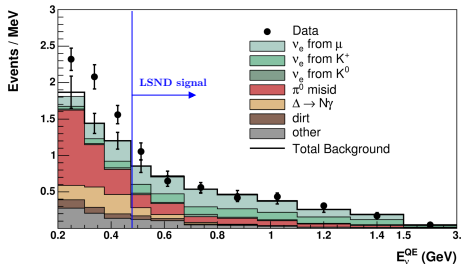
$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$

$\nu_\mu \rightarrow \nu_e$

[PRL 102 (2009) 101802]

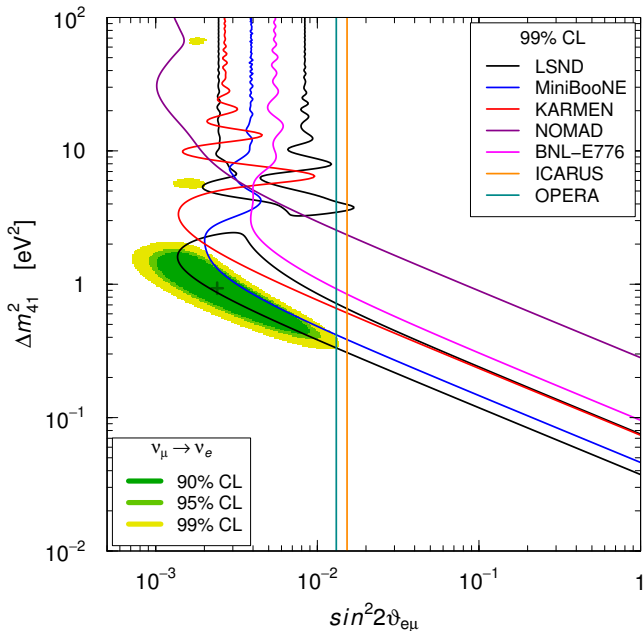
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

[PRL 110 (2013) 161801]

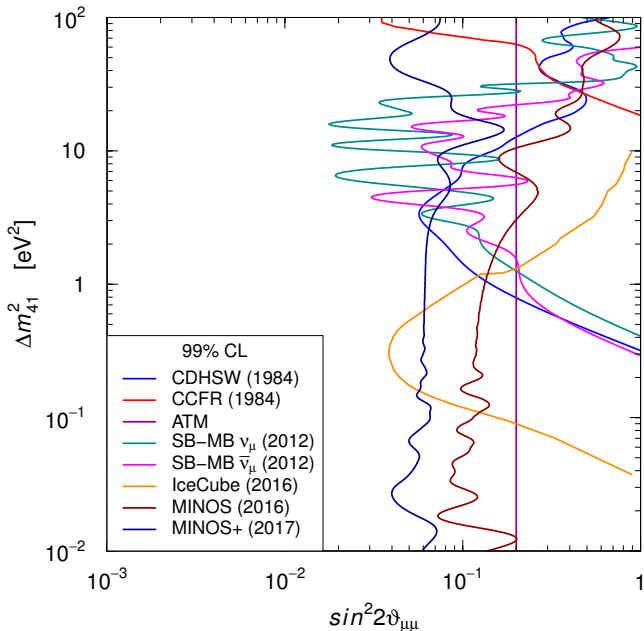


- ▶ Purpose: check LSND signal.
- ▶ Different L and E .
- ▶ Similar L/E (oscillations).
- ▶ No money, no Near Detector.
- ▶ LSND signal: $E > 475 \text{ MeV}$.
- ▶ Agreement with LSND signal?
- ▶ Low-energy anomaly \Rightarrow MicroBooNE
- ▶ Pragmatic Approach: $E > 475 \text{ MeV}$.

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



ν_μ and $\bar{\nu}_\mu$ Disappearance

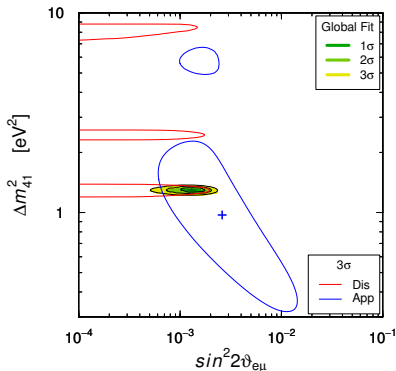


3+1 Appearance-Disappearance Tension

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

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

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

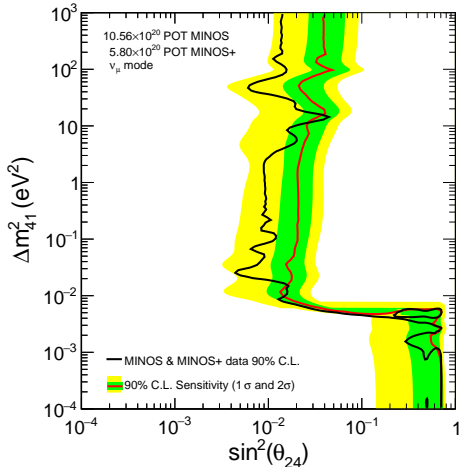
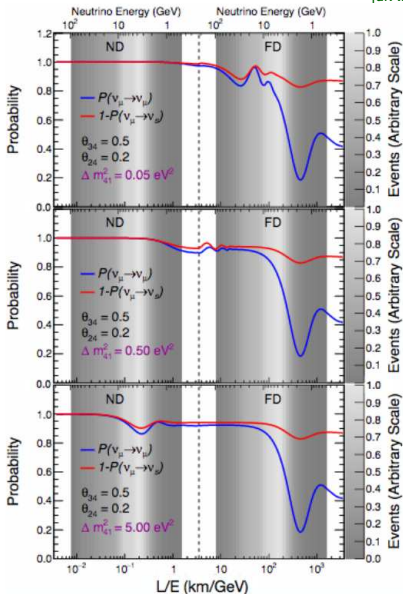


- ▶ $\nu_\mu \rightarrow \nu_e$ is quadratically suppressed!
- ▶ Global Fit without MINOS+
 $\chi_{\text{PG}}^2/\text{NDF}_{\text{PG}} = 5.5/2 \Rightarrow \text{GoF}_{\text{PG}} = 6.5\%$
- ▶ Similar tension in 3+2, 3+3, ..., 3+ N_s

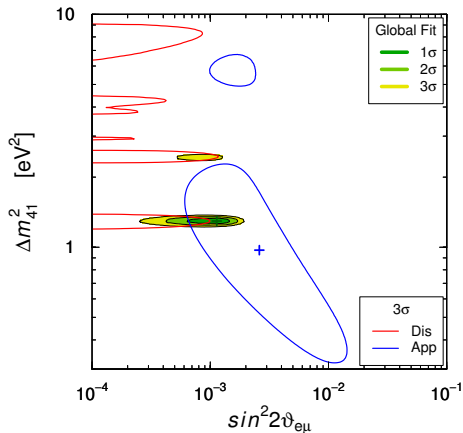
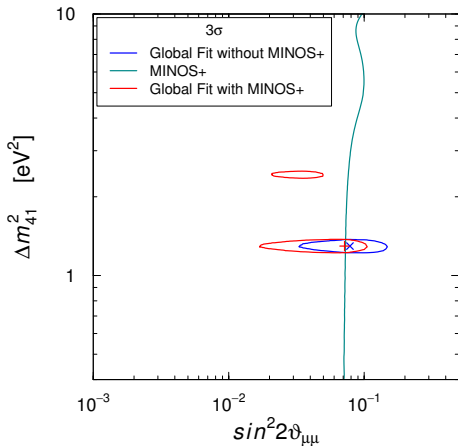
[CG, Zavanin, MPLA 31 (2015) 1650003]

New Bound from MINOS+

[arXiv:1710.06488]



Effects of MINOS+



- ▶ $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 14.6/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.07\% \leftarrow$ Intolerable tension!
- ▶ The MINOS+ bound (if correct) disfavors the LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal.

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

Conclusions

- ▶ Exciting **model-independent** indication of light sterile neutrinos at the eV scale from the **NEOS** and **DANSS** experiments \implies **New Physics beyond the Standard Model!**
- ▶ Agreement with the Reactor and Gallium Anomalies \implies 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**) and $\beta\beta_{0\nu}$ -decay.
- ▶ The MINOS+ bound (if correct) disfavors the LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal.