Status of eV-scale Sterile Neutrinos

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From the Planck Scale to the Weak Scale

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Neutrino Oscillations

$$\boxed{\nu_{\alpha L} = \sum_k U_{\alpha k} \nu_{kL}} \qquad \alpha = e, \mu, \tau$$

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

$$+ 2 \underbrace{\sum_{k>j} \text{Im}\left[U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^*\right] \sin\left(\frac{\Delta m_{kj}^2 L}{2E}\right)}_{\text{CP violating}}$$

- 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: $J_{\text{CP}} = \text{Im}\left[U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^*\right]$

Three-Neutrino Mixing Paradigm

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

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

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

(KamLAND)

$\to$

$$\Delta m^2_S = \Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\text{eV}^2$$
$$\sin^2\vartheta_S = \sin^2\vartheta_{12} \simeq 0.30$$

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

LBL Accelerator
ν_μ disappearance

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

Super-Kamiokande
Kamiokande, IMB
MACRO, Soudan-2

K2K, MINOS
T2K, NOνA

(Opera)

$\to$

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

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

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

(T2K, MINOS, NOνA)

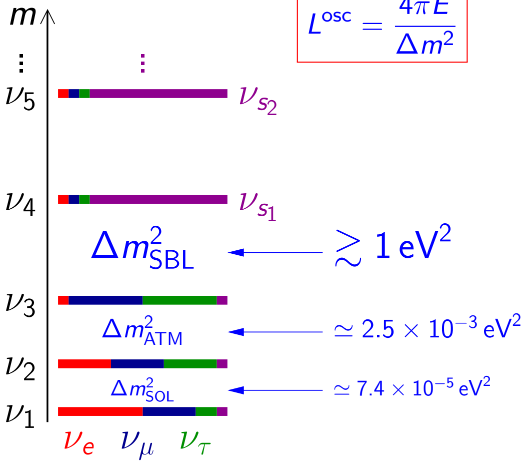
Daya Bay, RENO
Double Chooz

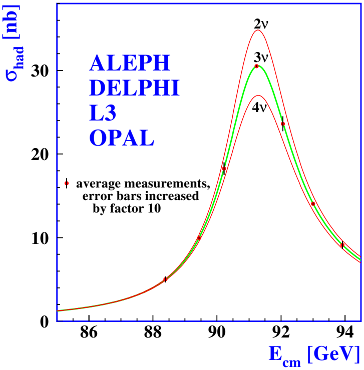
$\to$

$$\Delta m^2_A = |\Delta m^2_{31}|$$
$$\sin^2\vartheta_{13} \simeq 0.022$$

Beyond Three-Neutrino Mixing: Sterile Neutrinos

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





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

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) $\leftarrow$ CEνNS
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + 3ν-mixing:

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

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]

3+1: Appearance vs Disappearance

- 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:

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

- Amplitude of $\nu_\mu \to \nu_e$ 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 $|U_{\mu4}|^2$

$\Downarrow$

Appearance-Disappearance Tension

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

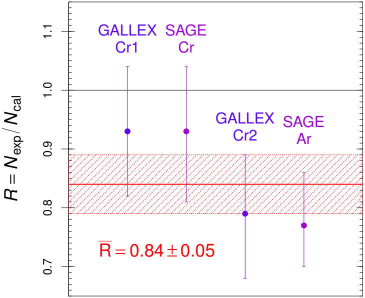
Gallium Anomaly

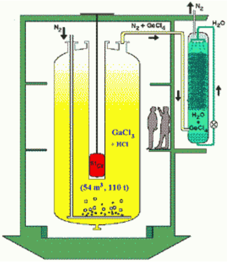
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

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





$\approx 2.9\sigma$ deficit

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

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

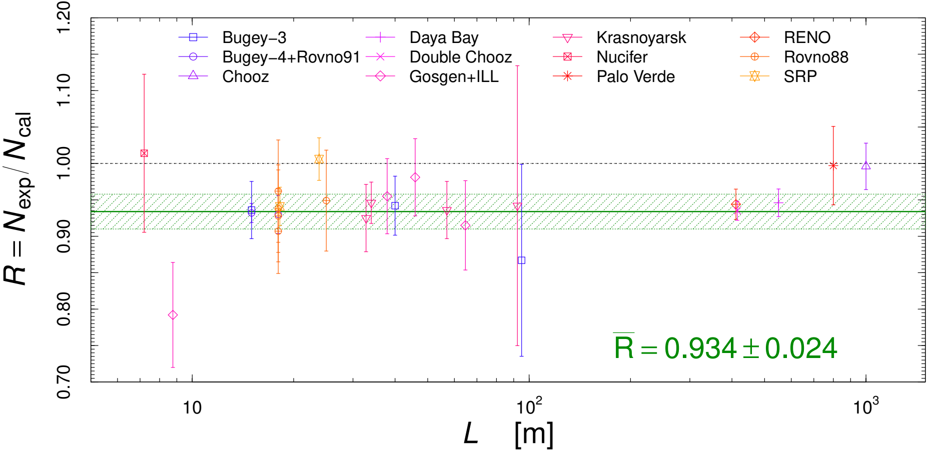
[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807; Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344, MPLA 22 (2007) 2499, PRD 78 (2008) 073009, PRC 83 (2011) 065504]

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

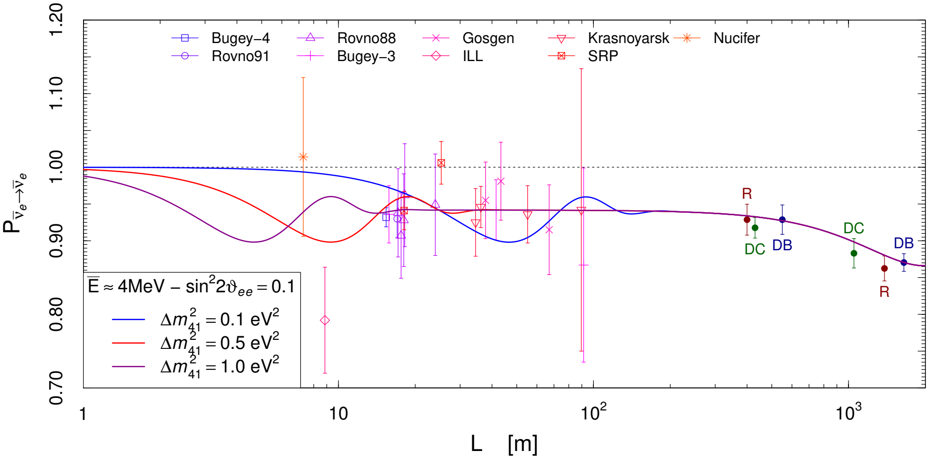
Reactor Electron Antineutrino Anomaly

[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]



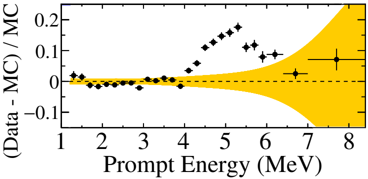
$\approx 2.8\sigma$ deficit



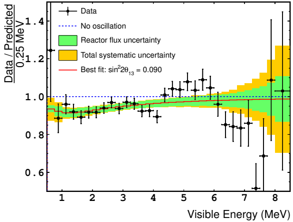
$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$$

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

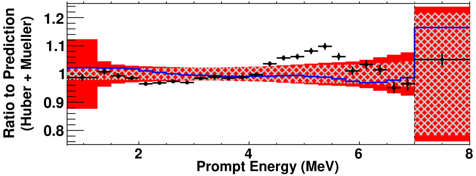
Reactor Antineutrino 5 MeV Bump



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]

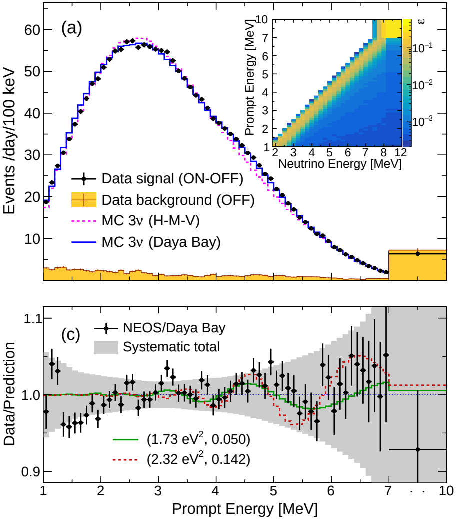


[Daya Bay, arXiv:1508.04233]

- Cannot be explained by neutrino oscillations (SBL oscillations are averaged in 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)]

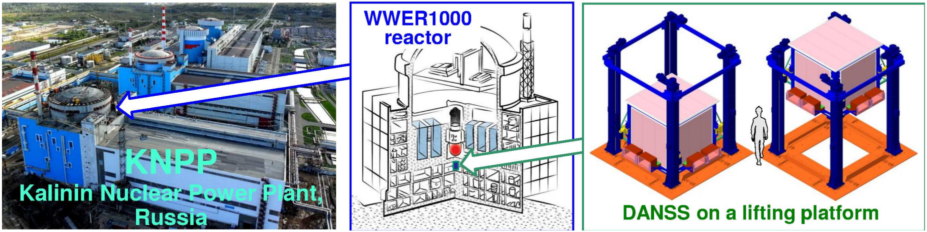


- Hanbit Nuclear Power Complex in Yeong-gwang, Korea.
- Thermal power of 2.8 GW.
- Detector: a ton of Gd-loaded liquid scintillator in a gallery approximately 24 m from the reactor core.
- The measured antineutrino event rate is 1976 per day with a signal to background ratio of about 22.

DANSS

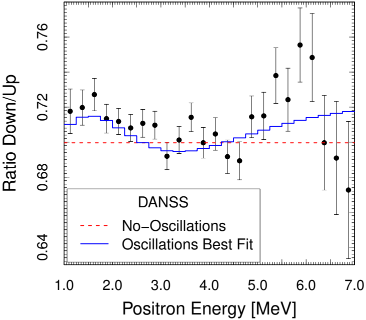
[Danilov @ Solvay Workshop, 1 December 2017, and La Thuile 2018, 3 March 2018]

Detector of reactor AntiNeutrino based on Solid Scintillator



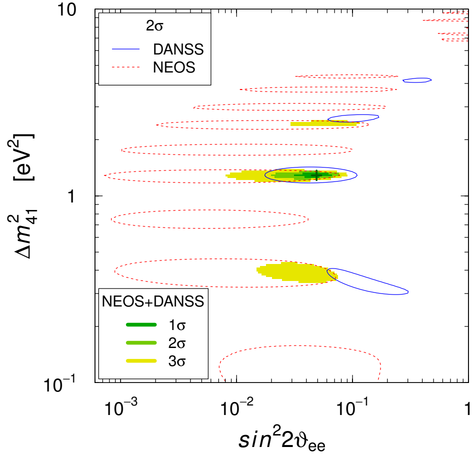
- Installed on a movable platform under a 3 GW reactor.
- Large neutrino flux.
- Reactor shielding of cosmic rays.
- Variable source-detector distance with the same detector!

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



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

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



$\sim 3.7\sigma$

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

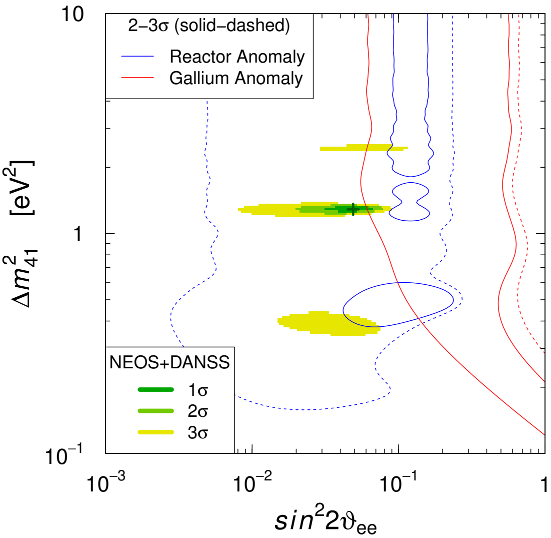
$\sin^2 2\vartheta_{ee} = 0.049 \pm 0.011$

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

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

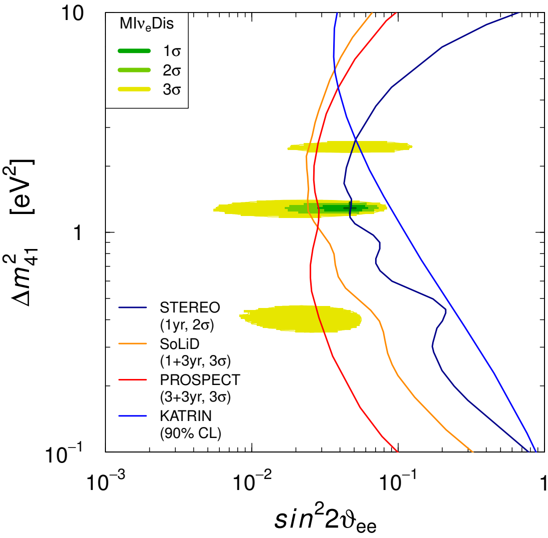
$\sin^2 \vartheta_{13} = 0.022 \pm 0.001$

Comparison with the Reactor and Gallium Anomalies



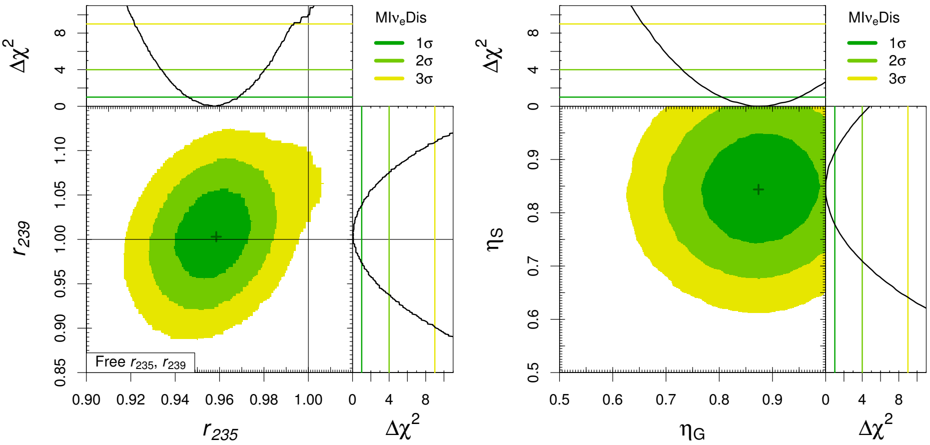
- 3σ agreement.
- 2σ tension.
- Small overestimate of the reactor fluxes.
- Small overestimate of the GALLEX and SAGE efficiencies.

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.

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

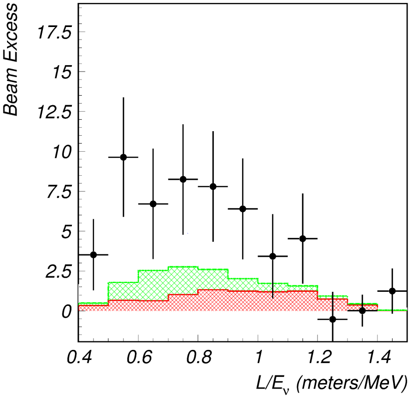


- Indication of $r_{235} < 1$.
- Likely small overestimate of the GALLEX and SAGE efficiencies.

LSND

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

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



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

- 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 $\bar{\nu}_e$

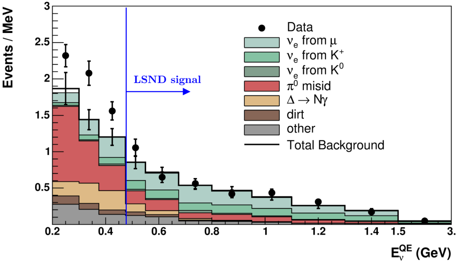
- $\approx 3.8\sigma$ excess
- But signal not seen by KARMEN at $L \simeq 18\,\text{m}$ with the same method

[PRD 65 (2002) 112001]

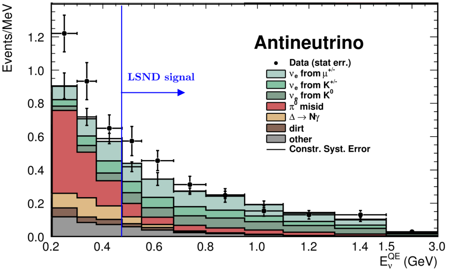
MiniBooNE

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

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

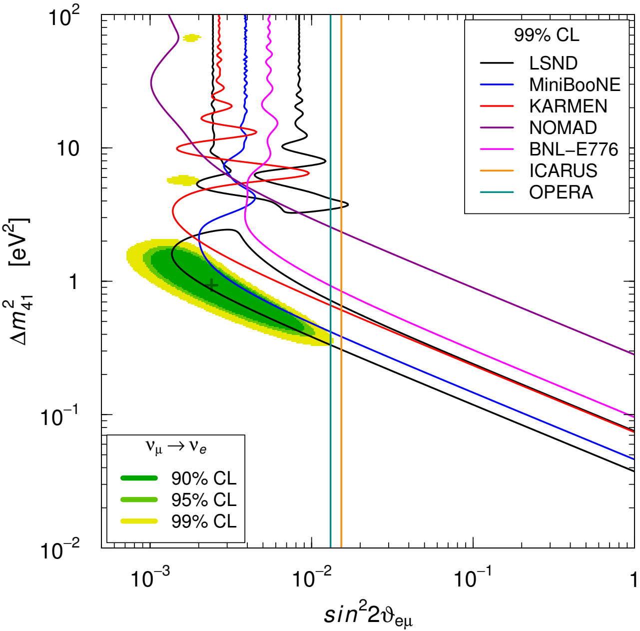


$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]

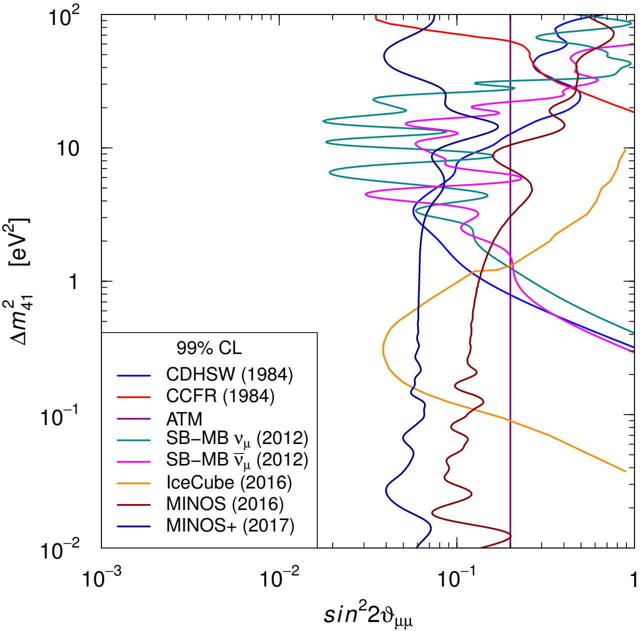


- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- No money, no Near Detector.
- LSND signal: $E > 475\,\text{MeV}$.
- Agreement with LSND signal?
- Low-energy anomaly $\Rightarrow$ MicroBooNE
- Pragmatic Approach: $E > 475\,\text{MeV}$.

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



ν_μ and $\bar{\nu}_\mu$ Disappearance



3+1 Appearance-Disappearance Tension

ν_e DIS

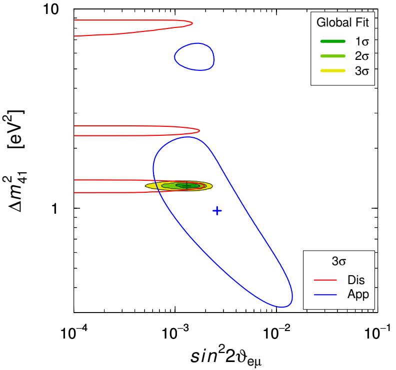
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

ν_μ DIS

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

$\nu_\mu \to \nu_e$ APP

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



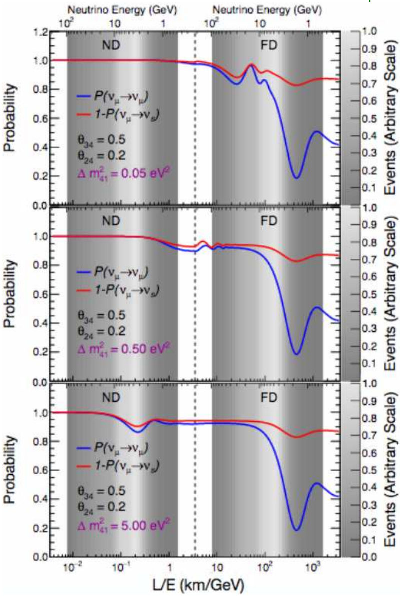
- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- Global Fit without MINOS+

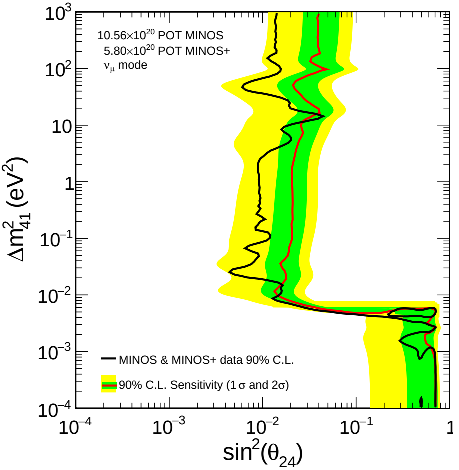
  $\chi^2_{PG}/\text{NDF}_{PG} = 5.5/2 \Rightarrow \text{GoF}_{PG} = 6.5\%$
- Similar tension in 3+2, 3+3, ..., $3+N_s$

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

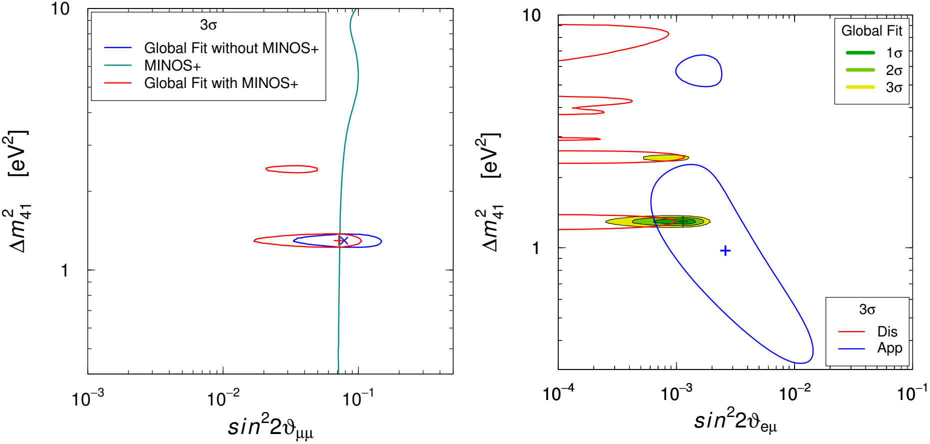
New Bound from MINOS+

[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 $\bar{\nu}_\mu \to \bar{\nu}_e$ 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 $\Longrightarrow$ 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, SoLid, and PROSPECT.

- Independent tests through effect of m_4 in β-decay (KATRIN, Holmium) and $\beta\beta_{0\nu}$-decay.

- The MINOS+ bound (if correct) disfavors the LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal.