Neutrino Oscillation Anomalies and their Relation to Sterile Neutrinos

6th KSETA Plenary Workshop 2019, Durbach

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Theoretical Astroparticle Physics, IKP

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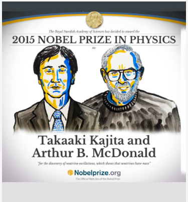
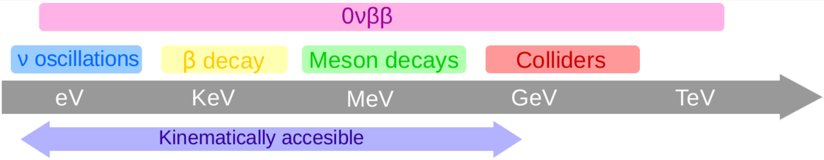
Neutrino Oscillations

2015 Nobel Prize
Arthur B. McDonald, Takaaki Kajita
For the discovery of neutrino oscillations, which shows that neutrinos have mass



New Physics and Sterile Neutrinos

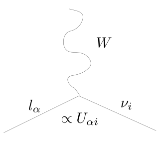


- 3ν Oscillations and global analysis
- Short Baseline Anomalies and the status of their interpretation in terms of Sterile Neutrino Oscillations

3ν Standard Oscillations

After EWSB: $\mathcal{L}_{CC} \propto U_{\alpha i} W_\mu^- \bar{\ell}_\alpha \gamma^\mu P_L \nu_i$

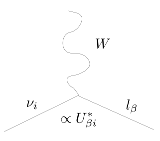
Lepton mixing matrix U, analogous to the CKM matrix.



$|\nu_\alpha\rangle = U_{\alpha j} |\nu_j\rangle$

Propagation

$$|\nu_\alpha(t)\rangle = U_{\alpha j} e^{-iE_j t} |\nu_j(t)\rangle = U_{\alpha j} e^{-iE_j t} U^*_{\gamma j} |\nu_\gamma\rangle$$

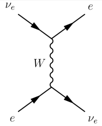


$|\nu_j\rangle = U^*_{\beta j} |\nu_\beta\rangle$

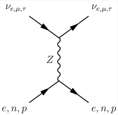
Oscillation Probability (in Vacuum)

$$P_{\nu_\alpha \to \nu_\beta} = \left|\langle \nu_\beta | \nu_\alpha(t)\rangle\right|^2 = \delta_{ab} - 4 \sum_{i>j} \mathrm{Re}\left(U_{aj} U^*_{bj} U^*_{ai} U_{bi}\right) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2 \sum_{i>j} \mathrm{Im}\left(U_{aj} U^*_{bj} U^*_{ai} U_{bi}\right) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

Neutrino oscillations in matter



(a) CC interaction.



(b) NC interaction.

CC effective potential

- Oscillation probability enhancement, MSW effect.
- intrinsic CP violation.

NC effective potential do not have any effect

Neutrino Oscillations

PMNS Matrix Parametrization

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad ; \quad \Delta m^2_{\rm atm}\,,\ \Delta m^2_{\rm sol} \quad \& \quad U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_1} & 0 \\ 0 & 0 & e^{-i\alpha_2} \end{pmatrix}$$

$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta}(E, L, \theta)$ **6 Parameters**: $\theta_{12},\ \theta_{23},\ \theta_{13}\ \delta_{CP},\ \Delta m^2_{sol} \ll \Delta m^2_{atm}$.

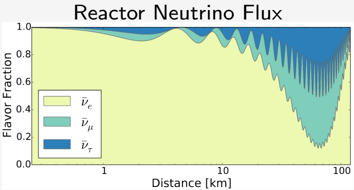
Oscillation Regimes

$$\frac{\Delta m^2 E}{4L} \simeq 1.27 \Delta m^2_{ij}(\mathrm{eV}^2) \frac{L(\mathrm{Km})}{E(\mathrm{GeV})}$$

$$\Delta m^2_{\rm sol} \sim 10^{-4}\mathrm{eV}^2 \ \Rightarrow \quad L/E \sim 10^4 \mathrm{Km/GeV}$$

Reactors: $E \sim \mathrm{MeV}$, $L \sim 1\mathrm{Km}$ Daya Bay

$L \sim 100\mathrm{Km}$ KamLAND



P.Vogel et.al. [arXiv:1503.01059]

Neutrino Oscillations, 3ν NuFit combined analysis

NuFIT 4.0 (2018), www.nu-fit.org I. Esteban, C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni, T. Schwetz

$$\chi^2(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{\mathrm{sol}}, \Delta m^2_{\mathrm{atm}}) =$$

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$$P_{\mathrm{KLAND}} = \sin^4\theta_{13} + \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2(2\theta_{12})\sin^2\frac{\Delta_{\mathrm{sol}}L}{4E}\right)$$

$\chi^2(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{\mathrm{sol}}, \Delta m^2_{\mathrm{atm}}) =$

$\chi^2_{\mathrm{sol+KLAND}}(\theta_{12}, \Delta m^2_{\mathrm{sol}}, \theta_{13})$

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P_{\mathrm{reactor}} &= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta_{\mathrm{sol}}L}{4E} - \\
&\quad \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta_{32}L}{4E}\right)
\end{aligned}
$$

$$
\begin{aligned}
& \chi^2(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{\mathrm{sol}}, \Delta m^2_{\mathrm{atm}}) = \\
& \chi^2_{\mathrm{sol+KLAND}}(\theta_{12}, \Delta m^2_{\mathrm{sol}}, \theta_{13}) \\
+ \quad & \chi^2_{\mathrm{reactor}}(\theta_{12}, \Delta m^2_{\mathrm{sol}}, \theta_{13}, \Delta m^2_{\mathrm{atm}})
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+ \quad &\chi^2_{\mathrm{reactor}}(\theta_{12}, \Delta m^2_{\mathrm{sol}}, \theta_{13}, \Delta m^2_{\mathrm{atm}}) \\
+ \quad &\chi^2_{\mathrm{LBL}}(\theta_{12}, \Delta m^2_{\mathrm{sol}}, \theta_{13}, \Delta m^2_{\mathrm{atm}}, \theta_{23}, \delta_{CP})
\end{aligned}
$$

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$$\begin{aligned}
&\chi^2(\theta_{12},\theta_{23},\theta_{13},\delta_{CP},\Delta m^2_{\mathrm{sol}},\Delta m^2_{\mathrm{atm}}) = \\
&\chi^2_{\mathrm{sol+KLAND}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13}) \\
+\;&\chi^2_{\mathrm{reactor}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13},\Delta m^2_{\mathrm{atm}}) \\
+\;&\chi^2_{\mathrm{LBL}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13},\Delta m^2_{\mathrm{atm}},\theta_{23},\delta_{CP}) \\
+\;&\chi^2_{\mathrm{atm}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13},\Delta m^2_{\mathrm{atm}},\theta_{23},\delta_{CP})
\end{aligned}$$

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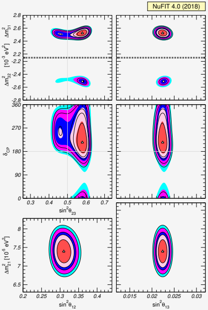
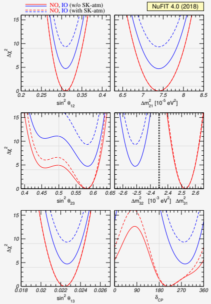
Combined analysis:

$$\begin{aligned}\chi^2(\theta_{12},\theta_{23},\theta_{13},\delta_{CP},\Delta m^2_{\mathrm{sol}},\Delta m^2_{\mathrm{atm}}) = \\ \chi^2_{\mathrm{sol+KLAND}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13}) \\ + \quad \chi^2_{\mathrm{reactor}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13},\Delta m^2_{\mathrm{atm}}) \\ + \quad \chi^2_{\mathrm{LBL}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13},\Delta m^2_{\mathrm{atm}},\theta_{23},\delta_{CP}) \\ + \quad \chi^2_{\mathrm{atm}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13},\Delta m^2_{\mathrm{atm}},\theta_{23},\delta_{CP})\end{aligned}$$



I.Esteban et.al. [arXiv:1811.05487]



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6 Parameters: θ_{12}, θ_{23}, θ_{13} & δ_{CP}

$\Delta m^2_{sol} \ll \Delta m^2_{atm}$ (Mass ordering)

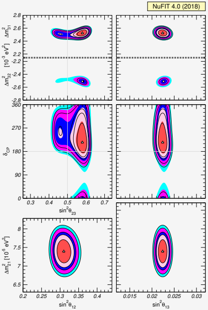
$m1 < m2 < m3$

$m3 < m1 < m2$

www.nu-fit.org

Combined analysis:

$$\chi^2(\theta_{12},\theta_{23},\theta_{13},\delta_{CP},\Delta m^2_{\mathrm{sol}},\Delta m^2_{\mathrm{atm}}) = \chi^2_{\mathrm{sol+KLAND}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13}) + \chi^2_{\mathrm{reactor}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13},\Delta m^2_{\mathrm{atm}}) + \chi^2_{\mathrm{LBL}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13},\Delta m^2_{\mathrm{atm}},\theta_{23},\delta_{CP}) + \chi^2_{\mathrm{atm}}(\theta_{12},\Delta m^2_{\mathrm{sol}},\theta_{13},\Delta m^2_{\mathrm{atm}},\theta_{23},\delta_{CP})$$



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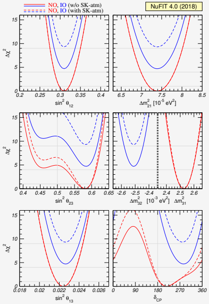


I.Esteban et.al. [arXiv:1811.05487]

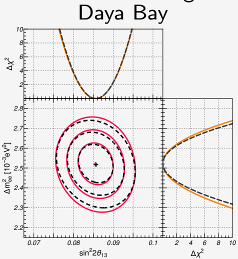
Predictions

$$N_i^d = \mathcal{N} \sum_r \sum_{\text{iso}} \frac{\epsilon^d}{L_{rd}^2} \int_{E_i^{\text{rec}}}^{E_{i+1}^{rec}} dE^{\text{rec}} \int_0^\infty dE_\nu\, \sigma(E_\nu) f^{\text{iso}} \phi^{\text{iso}}(E_\nu) P^{rd}_{\bar\nu_e \to \bar\nu_e}(E_\nu) R(E^{\text{rec}}, E_\nu)$$

Analysis, Pull approach

$$\chi^2(\boldsymbol{\theta}, \boldsymbol{\eta}) = \sum_{i,j} \frac{(Obs_i - Pred_i(\boldsymbol{\theta}, \boldsymbol{\eta}))^2}{(\sigma_i^{\text{stat}})^2} + \boldsymbol{\eta}_k V_{kl}^{-1} \boldsymbol{\eta}_l$$

$\boldsymbol{\eta}$: pull parameters accounting for the **systematics**. We include as much information from the collaborations as it is given.



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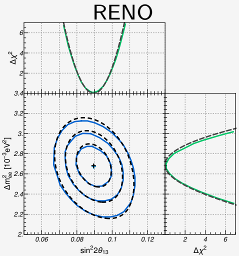

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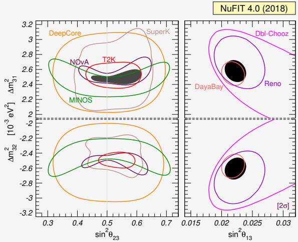

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Neutrino Oscillations

6 Parameters: θ_{12}, θ_{23}, θ_{13} & δ_{CP}

$\Delta m^2_{sol} \ll \Delta m^2_{atm}$ (Mass ordering)

$m1 < m2 < m3$

$m3 < m1 < m2$

3ν Oscillation Framework is very well tested

However there are experimental data that can not be accommodated in this framework

⇒ **Short Baseline Anomalies**

- Sterile Neutrino Oscillations
- Reactor Anti-neutrino Anomaly
- LSND and MiniBooNE Anomaly
- Appearance vs Disappearance Tension

$3 + 1\nu$ framework

$$P_{\overline{\nu}_e \to \overline{\nu}_e} = 1 - 4 \sum_{i=1}^{3} \sum_{j>i}^{4} \left|U_{ei}\right|^2 \left|U_{ej}\right|^2 \sin^2\left(\Delta m^2_{ij} \frac{L}{4E}\right)$$

$$P_{\overline{\nu}_e \to \overline{\nu}_e} \underset{\mathrm{SBL}}{\simeq} 1 - \sin^2 2\theta_{14} \sin^2\left(\Delta m^2_{41} \frac{L}{4E}\right)$$

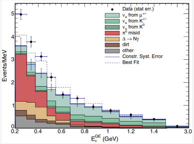
M.Dentler et.al. [arXiv:1803.10661]

M.Dentler, A.Hernandez-Cabezudo, J.Kopp, P.A.N.Machado, M.Maltoni, I.Martinez-Soler, T.Schwetz

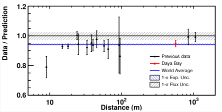
SBL Anomalies and Sterile Neutrino Oscillations

Short Baseline (SBL) Experiments measure in the **L/E** $\sim$ $\mathbf{1m/MeV}$ regime.
They are not sensitive to the 3ν standard oscillations ($\Delta m^2_{\rm atm}$ and $\Delta m^2_{\rm sol}$).

1. LNSD & MiniBooNE $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$
2. Gallium $\nu_e \rightarrow \nu_e$
3. Reactor $\bar{\nu}_e \rightarrow \bar{\nu}_e$



A.A. Aguilar-Arevalo et.al. [arXiv:1805.12028]

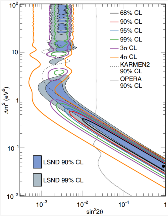


F.P. An et.al. [arXiv:1607.05378]

eV Sterile Neutrino

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \quad ; \quad \Delta m^2_{\rm new} \simeq 1{\rm eV}^2$$

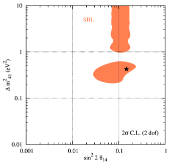
$$P^{\rm SBL}_{\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta} = \left| \delta_{\alpha\beta} - \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \right|$$



A.A. Aguilar-Arevalo et.al.

[arXiv:1805.12028]

Reactor Anomaly



Total measured events vs predicted events

Reactor Anti-neutrino Anomaly

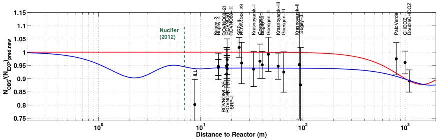
^{235}U, ^{239}Pu, ^{238}U & ^{241}Pu $\rightarrow \overline{\nu}_e$ ($\sim$MeV)Flux.

Reactor experiments measured a deficit $\bar{\nu_e}$ events with respect to the theoretical predictions (Huber-Muller)

Sterile Neutrino Oscillations

$$P_{\bar{\nu_e} \rightarrow \bar{\nu_e}} = 1 - \sin^2 2\theta_{14} \sin^2 \left(\frac{\Delta m^2_{\text{new}} L}{4E} \right)$$

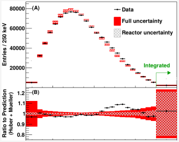
$$\text{averaged out} : P_{\bar{\nu_e} \rightarrow \bar{\nu_e}} = 1 - \frac{1}{2} \sin^2 2\theta_{14}$$



K. N. Abazajian et.al. [arXiv:1204.5379]

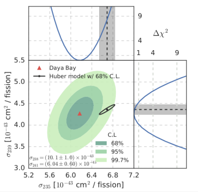
Flux Mismodelling

Daya Bay



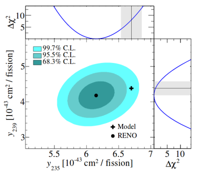
F. P. An et.al. [arXiv: 1607.05378]

Daya Bay



F. P. An et.al. [arXiv: 1704.01082]

RENO

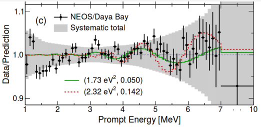


RENO cn. [arXiv: 1806.00574]

Global fit C.Giunti et.al. [arXiv: 1901.01807] of the flux evolution and all-time integrated $\bar{\nu_e}$ flux measurement do not favour the flux mismodeling hypothesis over the hybrid models.

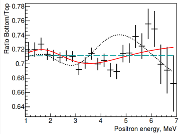
Recent New Data
Analysis independent of flux predictions

NEOS ($L \sim 24\mathrm{m}$)



Y.J. Ko et.al. [arXiv: 1610.05134]

DANSS ($L \sim 11\mathrm{m}$)

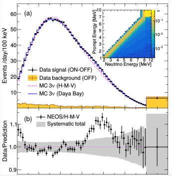


I Alekseev et.al. [arXiv: 1804.04046]

PROSPECT ($L \sim 7 - 13\mathrm{m}$)
STEREO ($L \sim 10\mathrm{m}$)
NEUTRINO 4* ($L \sim 6 - 12\mathrm{m}$)

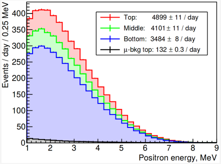
Based on ratios of measured spectra

NEOS spectrum



Y.J. Ko et.al. [arXiv: 1610.05134]

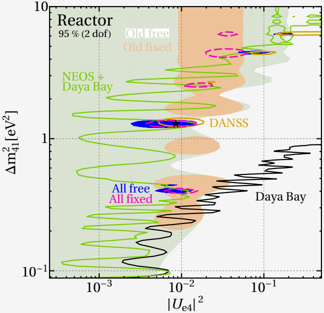
DANSS spectrum



I.Alekseev et.al. [arXiv: 1804.04046]

In our global analysis we perform a **Flux Free Analysis**, fitting the oscillation parameters as well as the normalizations of the flux predictions to the data.
M.Dentler et.al. [arXiv:1803.10661]

Reactor Global Analysis



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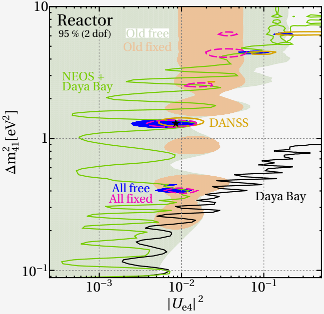

M.Dentler et.al. [arXiv:1803.10661]

Analysis	Δm^2_{41} [eV^2]	$\lvert U^2_{e4}\rvert$	χ^2_{min}/dof	$\Delta\chi^2$(no-osc)	significance
DANSS+NEOS	1.3	0.00964	74.4/(84 − 2)	13.6	3.3σ
all reactor (flux-free)	1.3	0.00887	185.8/(233 − 5)	11.5	2.9σ
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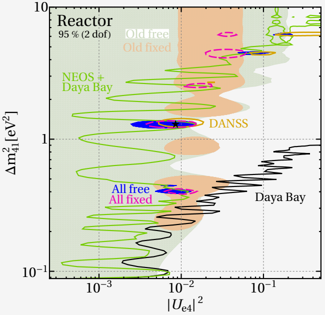

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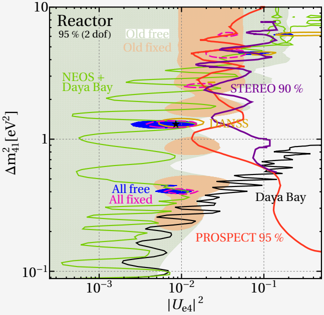
Reactor anomaly confirmed by ratios of measured spectra
independently of flux predictions

Reactor Anti-neutrino Anomaly

Reactor Global Analysis



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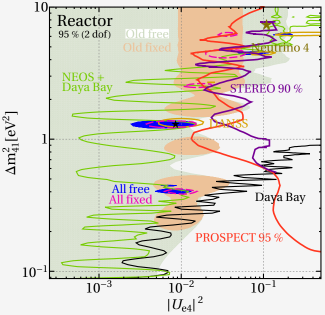

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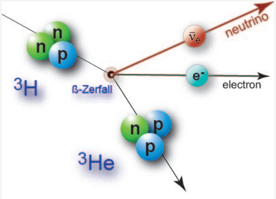
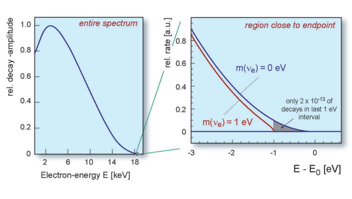
Reactor anomaly confirmed by ratios of measured spectra **independently** of flux predictions

Ractor Anti-neutrino Anomaly and KATRIN

$$\frac{d\Gamma}{dE} = \Theta\left(E_0 - E - m_\beta\right)\left(1 - |U_{e4}|^2\right)\frac{d\Gamma}{dE}\left(m_\beta\right) + \Theta\left(E_0 - E - m_4\right)|U_{e4}|^2\frac{d\Gamma}{dE}\left(m_4\right)$$



www.katrin.kit.edu



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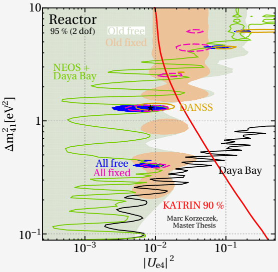
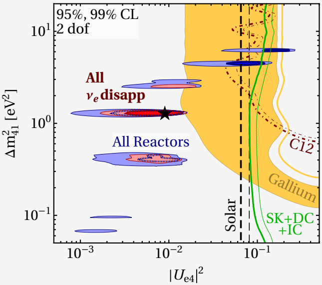


Marx Krozeczek, Master Thesis: *eV- & KeV-sterile neutrino studies with KATRIN*

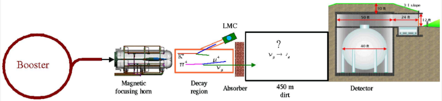
Global $\overset{(-)}{\nu}_e$ Disappearance Analysis



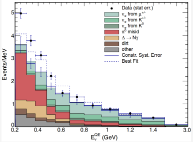
M.Dentler et.al. [arXiv:1803.10661]

Analysis	Δm^2_{41} [eV^2]	$\lvert U^2_{e4}\rvert$	χ^2_{min}/dof	$\Delta\chi^2$(no-osc)	significance
$\overset{(-)}{\nu}_e$ disap. (flux free)	1.3	0.00901	542.9/(594 − 8)	13.4	3.2σ

LNSD and MiniBooNE Anomalies, $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$



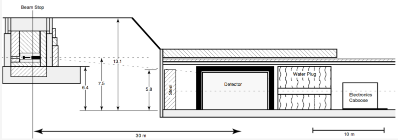
K. N. Abazajian et.al. [arXiv:1204.5379]



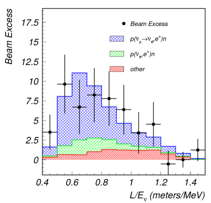
[arXiv:1805.12028]

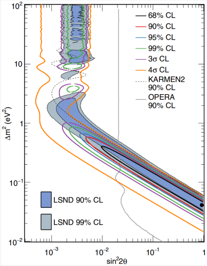
A.A. Aguilar-Arevalo et.al. [arXiv:1805.12028]

Oscillation regime $L/E \sim 0.15 - 2.3\ \mathrm{m/MeV}$



C.Athanassopoulos et.al. [arXiv:nucl-es/9605002]





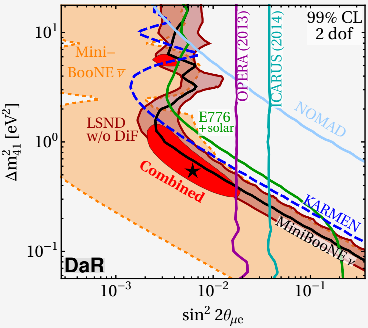
Oscillation regime $L/E \sim 0.5 - 1.5\ \mathrm{m/MeV}$

[arXiv:1204.5379]

LSND & MiniBooNE Anomalies

Global $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ Analysis

(Updated data till Spring 2018)



M.Dentler et.al. [arXiv:1803.10661]

$$\sin^2 2\theta_{\mu e} \propto |U_{\mu 4}|^2 |U_{e4}|^2$$

LSND & MiniBooNE Anomalies

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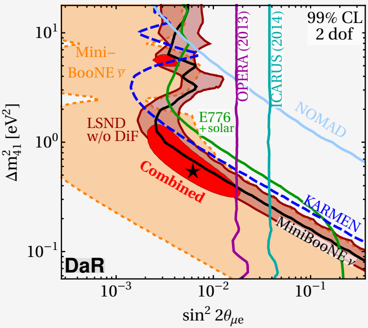


M.Dentler et.al. [arXiv:1803.10661]

$$P_{\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e} = 1 - 4|U_{e4}|^2(1-|U_{e4}|)^2 \sin^2\left(\frac{\Delta m^2_{41} E}{4L}\right)$$

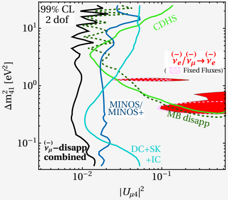
$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu} = 1 - 4|U_{\mu 4}|^2(1-|U_{\mu 4}|)^2 \sin^2\left(\frac{\Delta m^2_{41} E}{4L}\right)$$

$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} E}{4L}\right)$$

$$\sin^2 2\theta_{e\mu} \simeq \frac{1}{4}\sin^2 2\theta_{ee}\sin^2 2\theta_{\mu\mu}$$

$$\sin^2 2\theta_{\mu e} \propto |U_{\mu 4}|^2|U_{e4}|^2$$

Global $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ Analysis $\Rightarrow$



M.Dentler et.al. [arXiv:1803.10661]

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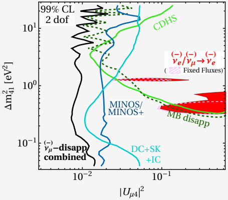
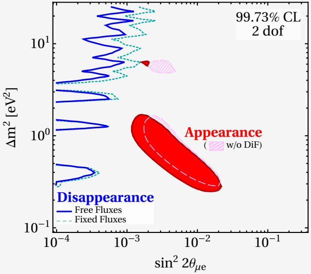


M.Dentler et.al. [arXiv:1803.10661]

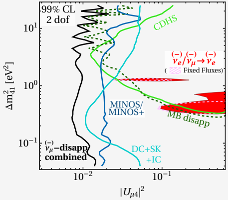
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ vs $\overset{(-)}{\nu}_\mu / \overset{(-)}{\nu}_e$ Tension



M.Dentler et.al. [arXiv:1803.10661]

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ Appearance vs $\overset{(-)}{\nu}_\mu/\overset{(-)}{\nu}_e$ Disappearance Tension

Global $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ Analysis $\Rightarrow$



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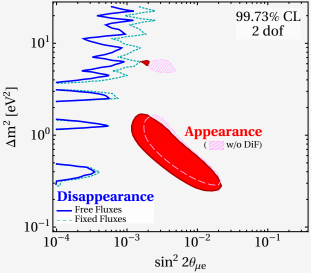


M.Dentler et.al. [arXiv:1803.10661]

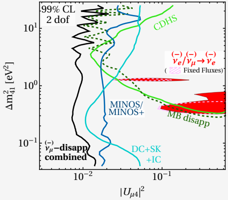
Parameter Goodness of Fit Test

Analysis	$\Delta\chi^2_{\text{app}-\text{disapp}}$	p-value	significance
Global	29.6	**3.7×10^{-7}**	5.1σ
w/o Reactors	20.3	3.9×10^{-5}	4.1σ

The tension is independent of the Reactor Anomaly

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ Appearance vs $\overset{(-)}{\nu}_\mu/\overset{(-)}{\nu}_e$ Disappearance Tension

Global $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ Analysis $\Rightarrow$



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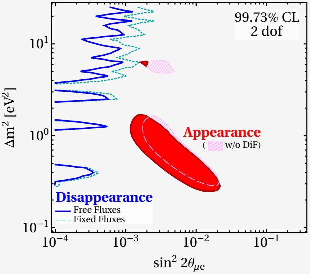
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ vs $\overset{(-)}{\nu}_\mu/\overset{(-)}{\nu}_e$ Tension



M.Dentler et.al. [arXiv:1803.10661]

Analysis	χ^2_{PG}/dof	PG
Global	29.6/2	3.71×10^{-7}
Removing anomalous data sets		
w/o LSND	12.9/2	1.6×10^{-3}
w/o MiniBooNE	24.4/2	5.2×10^{-6}
w/o reactors	20.3/2	3.8×10^{-5}
w/o gallium	33.9/2	4.4×10^{-8}
Removing constraints		
w/o IceCube	29.4/2	4.2×10^{-7}
w/o MINOS(+)	24.5/2	4.7×10^{-6}
w/o MB disapp	28.7/2	6.0×10^{-7}
w/o CDHS	28.2/2	7.5×10^{-7}

The tension is independent of any particular experiment

Summary

- 3ν Oscillations unknown parameters: δ_{CP}, mass ordering, θ_{23} octant.
- 3ν Oscillations are a very well tested framework. However there are some anomalies.
- Reactor Anti-neutrino anomaly is compatible with new data, independent of flux predictions, at the level of $\sim 3\sigma$: $|U_{e4}|^2 \sim 0.01$ and $\Delta m^2_{\rm new} \sim 1.3{\rm eV}^2$.
- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ Appearance data (MiniBooNE and LSND) is in strong tension with the Disappearance data ($\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ bounds), independently of the reactor data.
- MiniBooNE and LSND data should not be explained in terms of sterile neutrino oscillations.