Sterile Neutrino Global Fits

To Oscillation Experiments Data

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Neutrino oscillations: the broad picture

Neutrino oscillation is the phenomenon that the probability to detect a neutrino of flavour β, which was initially produced as flavour α, changes as a function of distance and inverse energy.

Neutrino oscillations: the broad picture

Neutrino oscillation theory

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \text{Re}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$
$$+2\sum_{i>j} \text{Im}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

- $U^*_{\alpha i}$ entries of the leptonic mixing matrix
- $\Delta m^2_{ij} := \Delta m^2_i - \Delta m^2_j$ squared differences between mass-eigenstates

Neutrino oscillations: the broad picture

Neutrino oscillation theory

Amplitude parameter

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Frequency parameter

- $U^*_{\alpha i}$ entries of the leptonic mixing matrix
- $\Delta m^2_{ij} := \Delta m^2_i - \Delta m^2_j$ squared differences between mass-eigenstates

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur McDonald

"for the discovery of neutrino oscillations"

NobelPrize.org. Nobel Media AB 2019

“Neutrino Physics is entering the precision era”

Neutrino oscillations: the broad picture

Precision test on neutrino oscillation theory

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$
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- measure at different baselines $\rightarow$ frequency parameter Δm^2_{ij}
- measure diffferent channels (and baselines) $\rightarow$ matrix elements $U^*_{\alpha i}$

Neutrino oscillations: the broad picture

Precision test on neutrino oscillation theory

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"With the exception of a few possible anomalies such as LSND, current neutrino data can be described within the framework of a 3×3 *mixing matrix between the flavor eigenstates* ν_e, ν_μ, *and* ν_τ *and the mass eigenstates* ν_1, ν_2, *and* ν_3*."*

M. Tanabashi et al., "Review of particle physics", Phys. Rev. D, 2018

Neutrino oscillations: the broad picture

Precision test on neutrino oscillation theory

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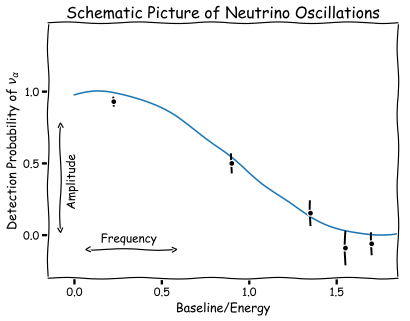
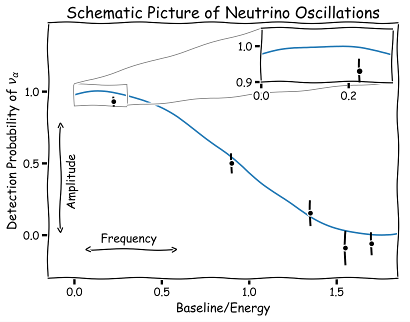


Neutrino oscillations: the broad picture

Precision test on neutrino oscillation theory

$$
\begin{aligned}
P_{\alpha\beta} =& \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) \\
&+2 \sum_{i>j} \mathrm{Im}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)
\end{aligned}
$$



Anomalies

The $\overset{(-)}{\nu}_e$ appearance channel: search for $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$

$\overset{(-)}{\nu}_e$ appearance channel

LSND Method:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow \mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

Baseline: $\mathcal{O}(30\,\text{m})$

Energy: $20 - 200\,\text{MeV}$

Aguilar++, "Evidence for neutrino oscillations from the observation of $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam", Phys. Rev., 2001

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$\Rightarrow \sim 3.8\sigma$ excess observed

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MiniBooNE Method: magnetized horns filter for either for *positive* or *negative* mesons:

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

Baseline: $\mathcal{O}(500\,\mathrm{m})$
Energy: $\mathcal{O}(500\,\mathrm{MeV})$

MiniBooNE Collaboration, Aguilar-Arevalo++, "Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment", arXiv:1805.12028

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Baseline: $\mathcal{O}(500\,\mathrm{m})$

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$\Rightarrow \sim 4.8\sigma$ excess observed

MiniBooNE Collaboration, Aguilar-Arevalo++, "Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment", arXiv:1805.12028

The $\overset{(-)}{\nu}_e$ disappearance channel:
search for
$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$

Reactor experiments Method: measure *total flux* of $\bar{\nu}_e$ from commercial reactors

Baseline: $\mathcal{O}(10 - 100\,\mathrm{m})$

Energy: $\mathcal{O}(\text{few MeV})$

Huber, "On the determination of anti-neutrino spectra from nuclear reactors", Phys.Rev. C, 2011
Mueller++, "Improved Predictions of Reactor Antineutrino Spectra", Phys.Rev. C, 2011

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Mueller++, "Improved Predictions of Reactor Antineutrino Spectra", Phys.Rev. C, 2011

$\overset{(-)}{\nu}_e$ disappearance channel

Gallium experiments Method: calibration of *gallium detectors* for solar neutrino measurements.
Radioactive source was placed inside detector, measure total flux of ν_e
Baseline: $\mathcal{O}(0.6, 1.6\,\mathrm{m})$
Energy: $\mathcal{O}(1\,\mathrm{MeV})$

Hampel++, "Final results of the Cr-51 neutrino source experiments in GALLEX", Phys. Lett. B, 1998
Abdurashitov++, "Measurement of the response of the Russian- American gallium experiment to neutrinos from a Cr-51 source", Phys.Rev. C, 1999
Abdurashitov++,"Measurement of the response of a Ga solar neutrino experiment to neutrinos from an Ar-37 source", Phys.Rev. C, 2006
Giunti++,"Matter Effects in Active-Sterile Solar Neutrino Oscillations", Phys. Rev. D, 2009
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Oscillations with sterile neutrinos

Neutrino oscillation theory

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$
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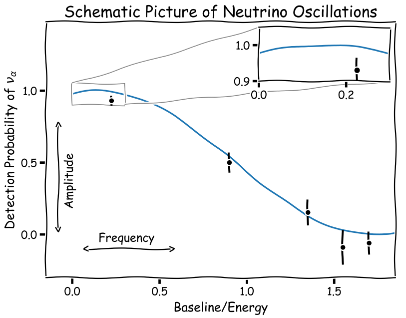
$$\alpha, \beta \in \{e, \mu, \tau\}$$



Oscillations with sterile neutrinos: a comic picture

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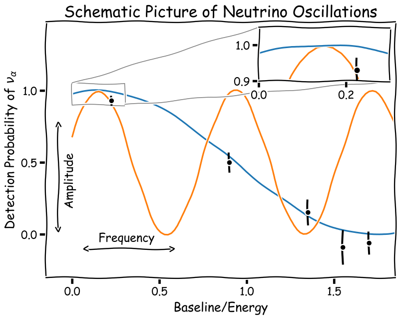

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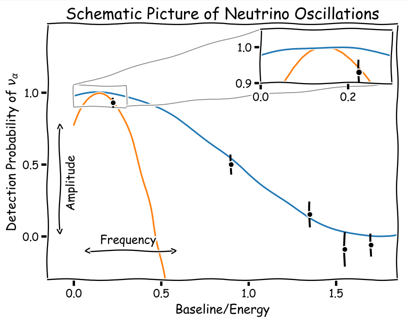

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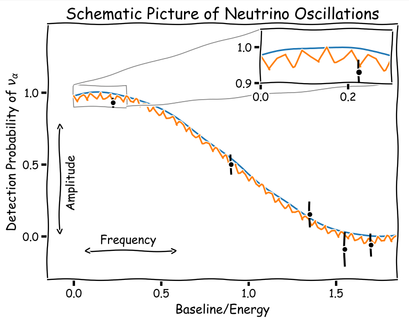

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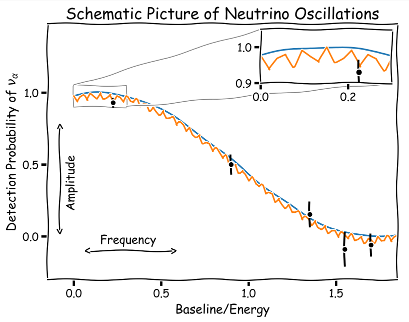

"sterile" flavour

no interaction

in the SM

Oscillations with sterile neutrinos: a comic picture

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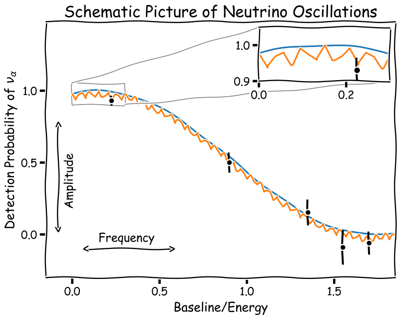

$\Delta m^2_{4i} \gg \Delta m^2_{31}, \Delta m^2_{32}, \Delta m^2_{21}$

Oscillations with sterile neutrinos: a comic picture

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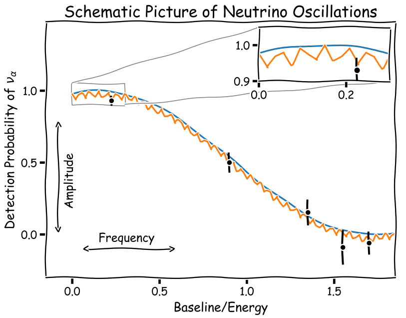


$\Delta m^2_{4i} \gg \Delta m^2_{31}, \Delta m^2_{32}, \Delta m^2_{21}$

- $L/4E \sim \mathcal{O}(1) \Rightarrow$ neglect $\Delta m^2_{31}, \Delta m^2_{32}, \Delta m^2_{21}$

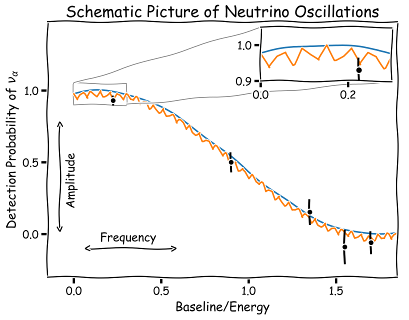
  Short Baseline Approximation

Oscillations with sterile neutrinos: a comic picture

Neutrino oscillation theory

$$P^{\mathrm{SBL}}_{\overset{(-)}{\alpha}\overset{(-)}{\alpha}} = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$P^{\mathrm{SBL}}_{\overset{(-)}{\alpha}\overset{(-)}{\beta}} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right) \qquad (\alpha \neq \beta).$$



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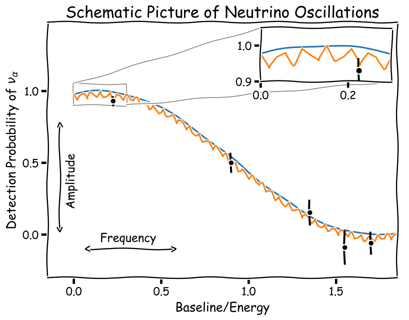
effective mixing parameter $\sin^2(2\theta_{\alpha\beta})$



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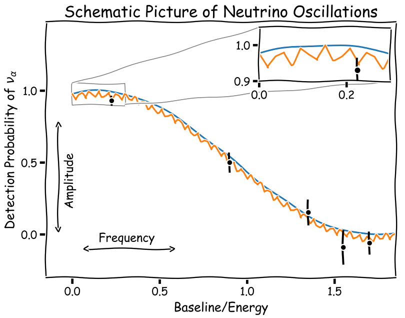

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- $L/4E \sim \mathcal{O}(1) \Rightarrow$ **neglect** $\Delta m^2_{31}, \Delta m^2_{32}, \Delta m^2_{21}$ **Short Baseline Approximation**
- $L/4E \gg 1 \Rightarrow$ all $\sin^2(\Delta m^2_{4j}L/(4E))$ **average out**

Realistic Evaluation

Can the observed anomalies be explained in the 3+1 framework?

- are the anomalies **compatible** with each other?
- could it be **SM systematics**?
- is a consistent explanation, **including all experiments**, possible the 3+1 framework?

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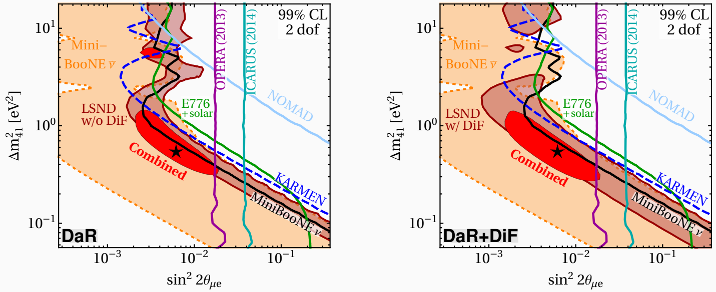
$\Rightarrow$ Global fits with sterile neutrino

Realistic Evaluation: $\overset{(-)}{\nu}_e$ appearance channel



Analysis	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\chi^2_{\min}/\text{DOF}$	GOF
appearance (DaR)	0.573	$4\lvert U_{e4}\rvert^2\lvert U_{\mu 4}\rvert^2 = 6.97\times 10^{-3}$		89.8/67	3.3%
appearance (DiF)	0.559	$4\lvert U_{e4}\rvert^2\lvert U_{\mu 4}\rvert^2 = 6.31\times 10^{-3}$		79.1/–	

MD, Hernández-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, "Updated Global Analysis of Neutrino Oscillations in the Presence of eV-Scale Sterile Neutrinos," JHEP, 2018

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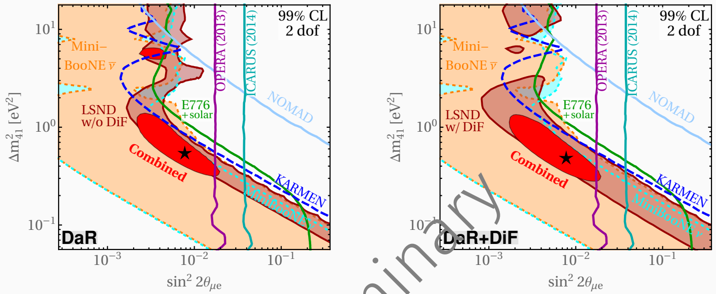
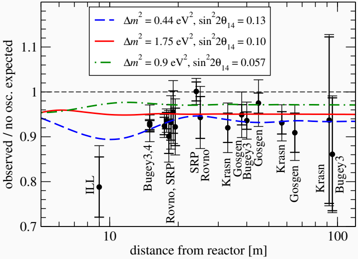


Analysis	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	χ^2_{min}/DOF	GOF
appearance (DaR)	0.562	$4\lvert U_{e4}\rvert^2\lvert U_{\mu 4}\rvert^2 = 7.76 \times 10^{-3}$		105.6/67	0.19%
appearance (DiF)	0.502	$4\lvert U_{e4}\rvert^2\lvert U_{\mu 4}\rvert^2 = 7.76 \times 10^{-3}$		96.2/–	

MD, Hernández-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, "Updated Global Analysis of Neutrino Oscillations in the Presence of eV-Scale Sterile Neutrinos," JHEP, 2018

Realistic Evaluation: flux uncertainties



Kopp++, "Sterile Neutrino Oscillations: The Global Picture", JHEP, 2013

Flux prediction

depends on

- Energy
- Fission isotope

Oscillation probability

depends on

- Energy
- Distance

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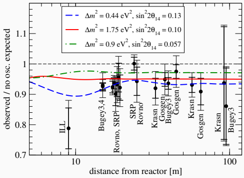

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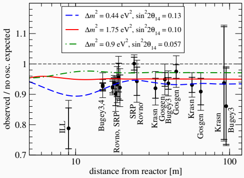
Disentangle hypotheses:

- measure **spectra** instead of **total rate**
- measure **ratios** between two points
- measure individual **fission isotopes**

Realistic Evaluation: flux uncertainties



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Evaluating the Daya Bay isotope flux measurement

Analysis	$\chi^2_{\text{min}}/\text{dof}$	gof	$\sin^2 2\theta_{14}^{\text{bfp}}$	$\Delta\chi^2(\text{no osc})$
fixed fluxes + ν_s	$9.8/(8-1)$	18%	0.11	3.9
free fluxes (no ν_s)	$3.6/(8-2)$	73%		

Assessment of DB's **preference for either hypothesis**:

Test statistic: $T = \chi^2_{min}(H_{Huber-Muller+\nu_s}) - \chi^2_{min}(H_{free\,fluxes})$

An++, "Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay", Phys. Rev. Lett.,2017

MD, Hernández-Cabezudo, Kopp, Maltoni,Schwetz, "Sterile neutrinos or flux uncertainties? – Status of the reactor anti-neutrino anomaly", JHEP, 2017

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$$T_{obs} = 6.3$$

p-value = 0.7% **(2.7σ)**

Both hypotheses remain valid $\Rightarrow$ two approaches:

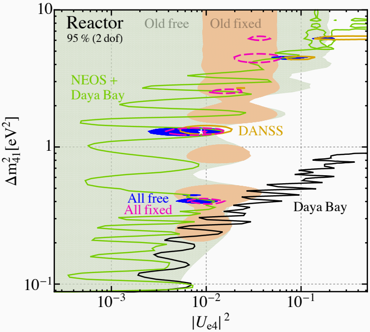
"flux-fixed"$\leftrightarrow$ "flux-free"

An++, "Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay", Phys. Rev. Lett.,2017
MD, Hernández-Cabezudo, Kopp, Maltoni,Schwetz, "Sterile neutrinos or flux uncertainties? – Status of the reactor anti-neutrino anomaly", JHEP, 2017

Realistic Evaluation: global reactor data

Data sets

Experiment	Comments
Bugey-4	rate
ILL	rate
Gösgen	rates
Krasnoyarsk	rates
Rovno88	rates
Rovno91	rate
SRP	rates
RENO	rate @ near detector + near-far rate ratio
Double Chooz	rate
Daya Bay flux	isotope flux
Bugey-3	3 spectra w. free norm
NEOS	spect. ratio NEOS/DayaBay
DANSS	spect. ratio at two L
Daya Bay spect.	spect. ratio EH3/EH1 & EH2/EH1
KamLAND	very distant spectrum



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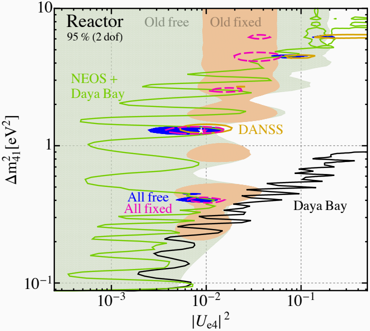
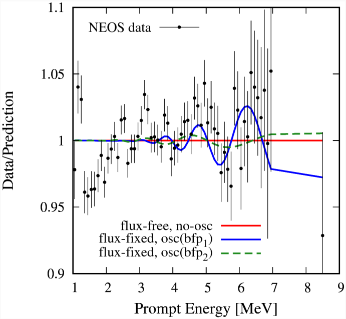
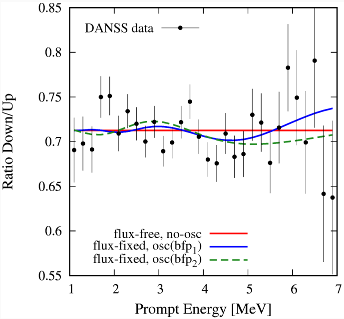


- fixed fluxes: hint for ν_s @ 3.5σ C.L.
- free fluxes: hint for ν_s @ 2.9σ C.L.
- hypothesis test: $T_{\text{obs}} = -1.3$
  $\Rightarrow$ preference for ν_s

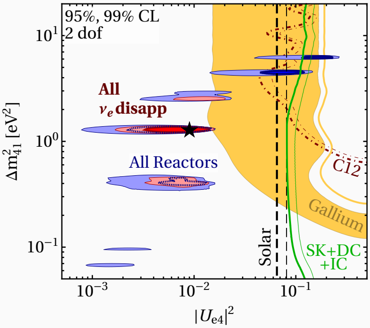
MD, Hernández-Cabezudo, Kopp, Maltoni, Schwetz, "Sterile neutrinos or flux uncertainties? – Status of the reactor anti-neutrino anomaly", JHEP, 2017

Realistic Evaluation: global reactor data





Realistic Evaluation: $\overset{(-)}{\nu}_e$ disappearance channel



MD, Hernández-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, "Updated Global Analysis of Neutrino Oscillations in the Presence of eV-Scale Sterile Neutrinos," JHEP, 2018

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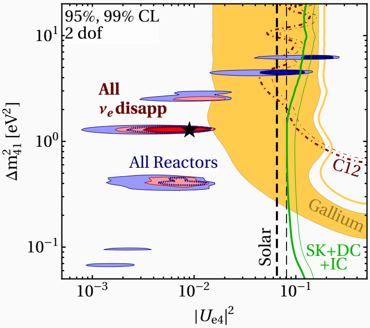

Analysis	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\chi^2_{\min}/\mathrm{DOF}$	GOF
$\overset{(-)}{\nu}_e$ disapp (flux fixed)	1.3	0.1	–	552.8/588	85%
$\overset{(-)}{\nu}_e$ disapp (flux free)	1.3	0.095	–	542.9/586	90%

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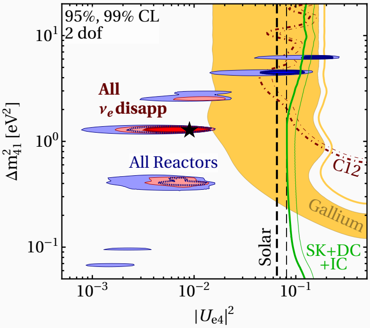

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2.2σ tension between Gallium and reactor preferred region

MD, Hernández-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, "Updated Global Analysis of

Realistic Evaluation: null results

Neutrino oscillation theory

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$
$$+2\sum_{i>j} \mathrm{Im}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

Realistic Evaluation: null results

Neutrino oscillation theory

$$P_{\alpha\alpha} = \delta_{\alpha\alpha} - 4\sum_{i>j} \mathrm{Re}\left[U^*_{\alpha i} U_{\alpha i} U_{\alpha j} U^*_{\alpha j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$
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- if signal in **disappearance channel**, e.g. $\alpha = \beta$, only row $U_{\alpha 1}$,$U_{\alpha 2}$, $U_{\alpha 3}$, $U_{\alpha 4}$ constrained

Realistic Evaluation: null results

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Realistic Evaluation: null results

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$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

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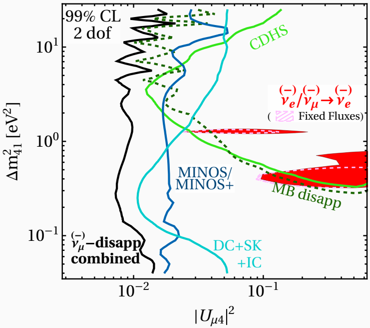
- if signal in **disappearance channel**, e.g. $\alpha = \beta$, only row $U_{\alpha 1}$,$U_{\alpha 2}$, $U_{\alpha 3}$, $U_{\alpha 4}$ constrained
- if signal in **appearance channel**, e.g. $\alpha \neq \beta$, **combinations** $U_{\alpha i} U_{\beta j}$ constrained
  $\Rightarrow$ signal in $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ **channel implies U_{e4}** and **$U_{\mu 4} \neq 0$**

Realistic Evaluation: $\overset{(-)}{\nu}_\mu$ disappearance channel



MD, Hernández-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, "Updated Global Analysis of Neutrino Oscillations in the Presence of eV-Scale Sterile Neutrinos," JHEP, 2018

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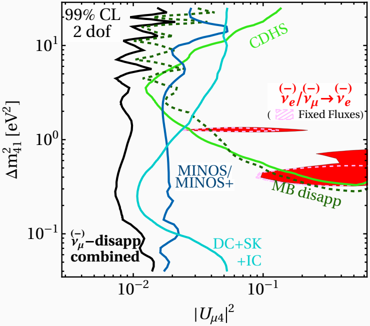

Analysis	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	χ^2_{min}/DOF	GOF
$\overset{(-)}{\nu}_\mu$ disapp	2×10^{-3}	0.12	0.039	468.9/497	81%

MD, Hernández-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, "Updated Global Analysis of Neutrino Oscillations in the Presence of eV-Scale Sterile Neutrinos," JHEP, 2018

3+1 global fit

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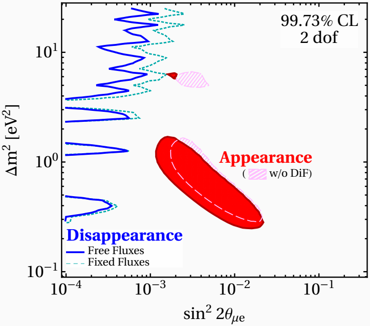
MD, Hernández-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, "Updated Global Analysis of Neutrino Oscillations in the Presence of eV-Scale Sterile Neutrinos," JHEP, 2018



Analysis	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	χ^2_{min}/DOF	GOF
Reactor fluxes fixed at predicted value $\pm$ quoted uncertainties					
Global (DiF)	6.03	0.2	0.1	1127/–	
Global (DaR)	5.99	0.21	0.12	1141/1159	64%
Reactor fluxes floating freely					
Global (DiF)	6.1	0.20	0.10	1121/–	
Global (DaR)	6.0	0.22	0.11	1134/1157	68%

3+1 global fit

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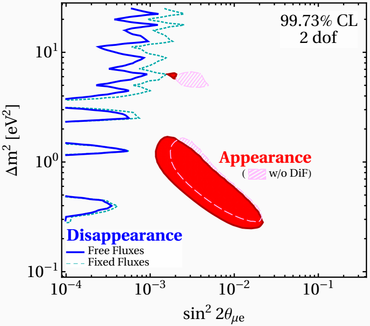

strong tension in data sets not reflected by GOF parameter

large number of data points is **not sensitive** to tension ⇒ "dilution" of GOF

Analysis	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\chi^2_{\min}$/DOF	GOF
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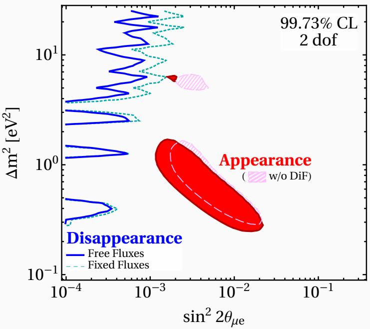

strong tension in data sets not reflected by GOF parameter

parameter goodness of fit (PG) test

$$\chi^2_{PG} \equiv \chi^2_{min,glob} - \chi^2_{min,app} - \chi^2_{min,dis}$$

Analysis	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\chi^2_{\min}$/DOF	GOF	PG
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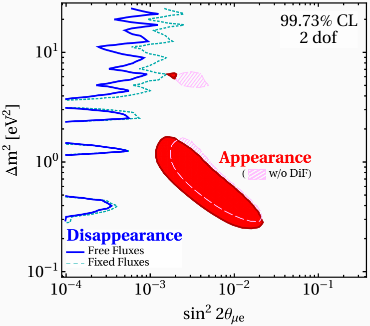

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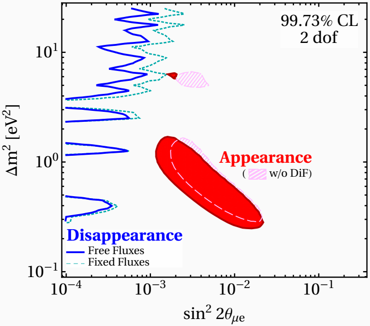

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tension at the 4.7σ level

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MD, Hernández-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, "Updated global analysis of neutrino oscillations in the presence of eV-scale sterile neutrinos," JHEP, 2018

How robust are these tensions?

Analysis	$\chi^2_{\text{min,global}}$	$\chi^2_{\text{min,app}}$	$\Delta\chi^2_{\text{app}}$	$\chi^2_{\text{min,disapp}}$	$\Delta\chi^2_{\text{disapp}}$	χ^2_{PG}/DOF	PG
Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.71×10^{-7}
Removing anomalous data sets							
w/o							
LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	1.6×10^{-3}
MiniBooNE	1012.2	40.7	8.3	947.2	16.1	24.4/2	5.2×10^{-6}
reactors	925.1	79.1	12.2	833.8	8.1	20.3/2	3.8×10^{-5}
gallium	1116.0	79.1	13.8	1003.1	20.1	33.9/2	4.4×10^{-8}
Removing constraints							
w/o							
IceCube	920.8	79.1	11.9	812.4	17.5	29.4/2	4.2×10^{-7}
MINOS/ MINOS+	1052.1	79.1	15.6	948.6	8.94	24.5/2	4.7×10^{-6}
MiniBooNE disap.	1054.9	79.1	14.7	947.2	13.9	28.7/2	6.0×10^{-7}
CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	7.5×10^{-7}
Removing classes of data							
$\overset{(-)}{\nu}_e$ disapp. vs $\overset{(-)}{\nu}_e$ app.	628.6	79.1	0.8	542.9	5.8	6.6/2	3.6×10^{-2}
$\overset{(-)}{\nu}_\mu$ disapp. vs $\overset{(-)}{\nu}_e$ app.	564.7	79.1	12.0	468.9	4.7	16.7/2	2.3×10^{-4}
$\overset{(-)}{\nu}_\mu$ disapp. + solar vs $\overset{(-)}{\nu}_e$ app.	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

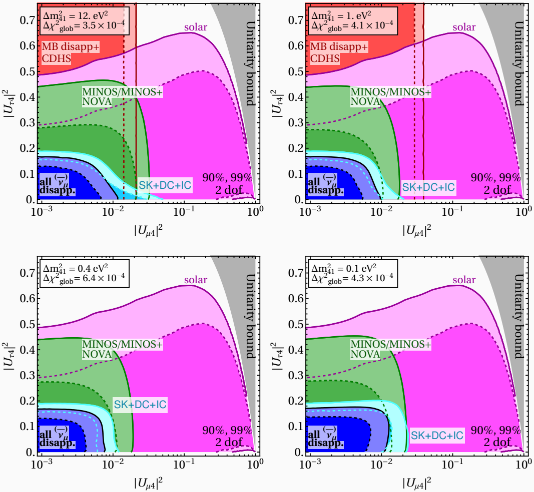
Conclusions

Conclusions

- the 3+1 framework provides a **straightforward** and **minimal** model for explaining anomalies in oscillation data
- within different channels, rather consistent (global) fits are possible
- new **reactor data** cannot definitely tell apart **3+1 oscillations and false flux predictions**
- the **strong tension** within the global data set; mainly driven by LSND, nearly independent from any individual remaining experiment;
- sterile neutrino oscillations might still be part of the explaination: either for **subset of data** or within **extended theoretical models**

Thank you!

Backup – constraints on $\overset{(-)}{\nu}_\tau$ oscillations



$$|U_{\tau 4}|^2 < 0.13\,(0.17) \quad \text{at} \quad 90\%\,(99\%)\text{ CL}$$

MD, Hernández-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, "Updated Global Analysis of Neutrino Oscillations in the Presence of eV-Scale Sterile Neutrinos," JHEP, 2018