Global Status of Sterile Neutrino Scenarios

Joachim Kopp

Max Planck Institut für Kernphysik, Heidelberg

XV International Workshop on Neutrino Telescopes
Venice, Italy March 13, 2012

MAX-PLANCK-GESELLSCHAFT

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

Outline

1. Theoretical Motivation
2. Sterile Neutrino Oscillations: The Global Picture
3. Sterile Neutrinos in Cosmology
4. Conclusions

Outline

1 Theoretical Motivation

2 Sterile Neutrino Oscillations: The Global Picture

3 Sterile Neutrinos in Cosmology

4 Conclusions

Sterile neutrinos


ster·ile *adjective* \ˈster-əl, *chiefly British* -ˌī(-ə)l\

Definition of STERILE

c : lacking in stimulating emotional or intellectual quality **:** LIFELESS <a *sterile* work of art>

. . . so why do we talk about sterile neutrinos?

Sterile neutrinos

Definition

Sterile neutrino = SM singlet fermion

- Very generic extension of the SM
  - can be leftovers of extended gauge multiplets (e.g. GUT multiplets)
- Very useful in phenomenology:
  - Can explain smallness of neutrino mass (seesaw mechanism, $m \sim \text{TeV} \dots M_{\text{Pl}}$)
  - Can explain baryon asymmetry of the Universe (leptogenesis, $m \gg 100$ GeV)
  - Can explain dark matter ($m \sim \text{keV}$)
  - Can explain various neutrino oscillation anomalies ($m \sim \text{eV}$) $\rightarrow$ This talk

eV-scale sterile neutrinos

Typical Lagrangian:

$$\mathcal{L} \supset \frac{1}{2} M^{(a)}_{ij} \overline{\nu^c_i} \nu_j + \frac{1}{2} M^{(s)}_{is} \overline{\nu^c_i} \nu_s + h.c.$$

$\Rightarrow$ mass mixing between active and sterile neutrinos

Signatures in oscillation experiments

- Disappearance of active neutrinos
  (e.g. $\nu_e \to \nu_s$ oscillations)
  Atmospheric, Solar, Reactor, Pion decay beam, Radioactive source experiments
- Anomalous transitions among active neutrinos ("appearance")
  (e.g. $\nu_\mu \to \nu_s \to \nu_e$)
  Pion decay beams
- Oscillation length $L^{\rm osc} = 4\pi E/\Delta m^2_{41}$ different from SM expectation (typically shorter)

Notation: $\Delta m^2_{jk} = m^2_j - m^2_k$; $m_{4,5}$: mostly sterile, $m_{1,2,3}$: mostly active

Neutrino oscillations with more than 3 flavours

Theoretical challenge: complicated dependence of observable oscillation probabilities on the fundamental parameters of the theory

3-flavour mixing matrix

$$\begin{pmatrix} \text{Cos}[\theta12]\ \text{Cos}[\theta13] & \text{Cos}[\theta13]\ \text{Sin}[\theta12] & e^{-i\,\delta0}\ \text{Sin}[\theta13] \\ -\text{Cos}[\theta23]\ \text{Sin}[\theta12] - e^{i\,\delta0}\ \text{Cos}[\theta12]\ \text{Sin}[\theta13]\ \text{Sin}[\theta23] & \text{Cos}[\theta12]\ \text{Cos}[\theta23] - e^{i\,\delta0}\ \text{Sin}[\theta12]\ \text{Sin}[\theta13]\ \text{Sin}[\theta23] & \text{Cos}[\theta13]\ \text{Sin}[\theta23] \\ -e^{i\,\delta0}\ \text{Cos}[\theta12]\ \text{Cos}[\theta23]\ \text{Sin}[\theta13] + \text{Sin}[\theta12]\ \text{Sin}[\theta23] & -e^{i\,\delta0}\ \text{Cos}[\theta23]\ \text{Sin}[\theta12]\ \text{Sin}[\theta13] - \text{Cos}[\theta12]\ \text{Sin}[\theta23] & \text{Cos}[\theta13]\ \text{Cos}[\theta23] \end{pmatrix}$$

Neutrino oscillations with more than 3 flavours

Theoretical challenge: complicated dependence of observable oscillation probabilities on the fundamental parameters of the theory

4-flavour mixing matrix

```
{{ Cos[θ12] Cos[θ13] Cos[θ14], e^(-i δ2) Cos[θ13] Cos[θ14] Sin[θ12], e^(-i δ0) Cos[θ14] Sin[θ13], Sin[θ14]},
 { - e^(i δ2) Cos[θ23] Cos[θ24] Sin[θ12] + Cos[θ12] ( - e^(i δ0) Cos[θ24] Sin[θ13] Sin[θ23] - e^(-i δ1) Cos[θ13] Sin[θ14] Sin[θ24]),
  e^(-i δ2) (e^(i δ2) Cos[θ12] Cos[θ23] Cos[θ24] + Sin[θ12] ( - e^(i δ0) Cos[θ24] Sin[θ13] Sin[θ23] - e^(-i δ1) Cos[θ13] Sin[θ14] Sin[θ24])),
  e^(-i δ0) (e^(i δ0) Cos[θ13] Cos[θ24] Sin[θ23] - e^(-i δ1) Sin[θ13] Sin[θ14] Sin[θ24]), e^(-i δ1) Cos[θ14] Sin[θ24]},
 { - e^(i δ2) Sin[θ12] ( - Cos[θ34] Sin[θ23] - e^(i δ1) Cos[θ23] Sin[θ24] Sin[θ34]) +
   Cos[θ12] ( - Cos[θ13] Cos[θ24] Sin[θ14] Sin[θ34] - e^(i δ0) Sin[θ13] (Cos[θ23] Cos[θ34] - e^(i δ1) Sin[θ23] Sin[θ24] Sin[θ34])),
  e^(-i δ2) (e^(i δ2) Cos[θ12] ( - Cos[θ34] Sin[θ23] - e^(i δ1) Cos[θ23] Sin[θ24] Sin[θ34]) +
    Sin[θ12] ( - Cos[θ13] Cos[θ24] Sin[θ14] Sin[θ34] - e^(i δ0) Sin[θ13] (Cos[θ23] Cos[θ34] - e^(i δ1) Sin[θ23] Sin[θ24] Sin[θ34]))),
  e^(-i δ0) ( - Cos[θ24] Sin[θ13] Sin[θ14] Sin[θ34] + e^(i δ0) Cos[θ13] (Cos[θ23] Cos[θ34] - e^(i δ1) Sin[θ23] Sin[θ24] Sin[θ34])), Cos[θ14] Cos[θ24] Sin[θ34]},
 { - e^(i δ2) Sin[θ12] ( - e^(i δ1) Cos[θ23] Cos[θ34] Sin[θ24] + Sin[θ23] Sin[θ34]) +
   Cos[θ12] ( - Cos[θ13] Cos[θ24] Cos[θ34] Sin[θ14] - e^(i δ0) Sin[θ13] ( - e^(i δ1) Cos[θ34] Sin[θ23] Sin[θ24] - Cos[θ23] Sin[θ34])),
  e^(-i δ2) (e^(i δ2) Cos[θ12] ( - e^(i δ1) Cos[θ23] Cos[θ34] Sin[θ24] + Sin[θ23] Sin[θ34]) +
    Sin[θ12] ( - Cos[θ13] Cos[θ24] Cos[θ34] Sin[θ14] - e^(i δ0) Sin[θ13] ( - e^(i δ1) Cos[θ34] Sin[θ23] Sin[θ24] - Cos[θ23] Sin[θ34]))),
  e^(-i δ0) ( - Cos[θ24] Cos[θ34] Sin[θ13] Sin[θ14] + e^(i δ0) Cos[θ13] ( - e^(i δ1) Cos[θ34] Sin[θ23] Sin[θ24] - Cos[θ23] Sin[θ34])), Cos[θ14] Cos[θ24] Cos[θ34]}}
```

Neutrino oscillations with more than 3 flavours

Theoretical challenge: complicated dependence of observable oscillation probabilities on the fundamental parameters of the theory

5-flavour mixing matrix

```
{{Cos[θ12] Cos[θ13] Cos[θ14] Cos[θ15], Cos[θ13] Cos[θ14] Cos[θ15] Sin[θ12], e^(-i δ0) Cos[θ14] Cos[θ15] Sin[θ13], e^(-i δ1) Cos[θ15] Sin[θ14], e^(-i δ2) Sin[θ15]},
 {-Cos[θ23] Cos[θ24] Cos[θ25] Sin[θ12] + Cos[θ12] (-e^(i δ0) Cos[θ24] Cos[θ25] Sin[θ13] Sin[θ23] + Cos[θ13] (-e^(i δ1) Cos[θ25] Sin[θ14] Sin[θ24] - e^(i δ2) Cos[θ14] Sin[θ15] Sin[θ25])),
  Cos[θ12] Cos[θ23] Cos[θ24] Cos[θ25] + Sin[θ12] (-e^(i δ0) Cos[θ24] Cos[θ25] Sin[θ13] Sin[θ23] + Cos[θ13] (-e^(i δ1) Cos[θ25] Sin[θ14] Sin[θ24] - e^(i δ2) Cos[θ14] Sin[θ15] Sin[θ25])),
  e^(-i δ0) (e^(i δ0) Cos[θ13] Cos[θ24] Cos[θ25] Sin[θ23] + Sin[θ13] (-e^(i δ1) Cos[θ25] Sin[θ14] Sin[θ24] - e^(i δ2) Cos[θ14] Sin[θ15] Sin[θ25])),
  e^(-i δ1) (e^(i δ1) Cos[θ14] Cos[θ25] Sin[θ24] - e^(i δ2) Sin[θ14] Sin[θ15] Sin[θ25]), Cos[θ15] Sin[θ25]}, {-Sin[θ12] (-Cos[θ34] Cos[θ35] Sin[θ23] + Cos[θ23] (-Cos[θ35] Sin[θ24] Sin[θ34] - Cos[θ24] Sin[θ25] Sin[θ35])) +
   Cos[θ12] (-e^(i δ0) Sin[θ13] (Cos[θ23] Cos[θ34] Cos[θ35] + Sin[θ23] (-Cos[θ35] Sin[θ24] Sin[θ34] - Cos[θ24] Sin[θ25] Sin[θ35])) +
     Cos[θ13] (-e^(i δ2) Cos[θ14] Cos[θ25] Sin[θ15] Sin[θ35] - e^(i δ1) Sin[θ14] (Cos[θ24] Cos[θ35] Sin[θ34] - Sin[θ24] Sin[θ25] Sin[θ35]))),
  Cos[θ12] (-Cos[θ34] Cos[θ35] Sin[θ23] + Cos[θ23] (-Cos[θ35] Sin[θ24] Sin[θ34] - Cos[θ24] Sin[θ25] Sin[θ35])) +
   Sin[θ12] (-e^(i δ0) Sin[θ13] (Cos[θ23] Cos[θ34] Cos[θ35] + Sin[θ23] (-Cos[θ35] Sin[θ24] Sin[θ34] - Cos[θ24] Sin[θ25] Sin[θ35])) +
     Cos[θ13] (-e^(i δ2) Cos[θ14] Cos[θ25] Sin[θ15] Sin[θ35] - e^(i δ1) Sin[θ14] (Cos[θ24] Cos[θ35] Sin[θ34] - Sin[θ24] Sin[θ25] Sin[θ35]))),
  e^(-i δ0) (e^(i δ0) Cos[θ13] (Cos[θ23] Cos[θ34] Cos[θ35] + Sin[θ23] (-Cos[θ35] Sin[θ24] Sin[θ34] - Cos[θ24] Sin[θ25] Sin[θ35])) +
    Sin[θ13] (-e^(i δ2) Cos[θ14] Cos[θ25] Sin[θ15] Sin[θ35] - e^(i δ1) Sin[θ14] (Cos[θ24] Cos[θ35] Sin[θ34] - Sin[θ24] Sin[θ25] Sin[θ35]))),
  e^(-i δ1) (-e^(i δ2) Cos[θ25] Sin[θ14] Sin[θ15] Sin[θ35] + e^(i δ1) Cos[θ14] (Cos[θ24] Cos[θ35] Sin[θ34] - Sin[θ24] Sin[θ25] Sin[θ35])), Cos[θ15] Cos[θ25] Sin[θ35]},
 {-Sin[θ12] (-Sin[θ23] (-Cos[θ45] Sin[θ34] - Cos[θ34] Sin[θ35] Sin[θ45]) + Cos[θ23] (-Cos[θ24] Cos[θ35] Sin[θ25] Sin[θ45] - Sin[θ24] (Cos[θ34] Cos[θ45] - Sin[θ34] Sin[θ35] Sin[θ45]))) +
   Cos[θ12] (Cos[θ13] (-e^(i δ2) Cos[θ14] Cos[θ25] Cos[θ35] Sin[θ15] Sin[θ45] - e^(i δ1) Sin[θ14] (-Cos[θ35] Sin[θ24] Sin[θ25] Sin[θ45] + Cos[θ24] (Cos[θ34] Cos[θ45] - Sin[θ34] Sin[θ35] Sin[θ45]))) -
     e^(i δ0) Sin[θ13] (Cos[θ23] (-Cos[θ45] Sin[θ34] - Cos[θ34] Sin[θ35] Sin[θ45]) + Sin[θ23] (-Cos[θ24] Cos[θ35] Sin[θ25] Sin[θ45] - Sin[θ24] (Cos[θ34] Cos[θ45] - Sin[θ34] Sin[θ35] Sin[θ45])))),
  Cos[θ12] (-Sin[θ23] (-Cos[θ45] Sin[θ34] - Cos[θ34] Sin[θ35] Sin[θ45]) + Cos[θ23] (-Cos[θ24] Cos[θ35] Sin[θ25] Sin[θ45] - Sin[θ24] (Cos[θ34] Cos[θ45] - Sin[θ34] Sin[θ35] Sin[θ45]))) +
   Sin[θ12] (Cos[θ13] (-e^(i δ2) Cos[θ14] Cos[θ25] Cos[θ35] Sin[θ15] Sin[θ45] - e^(i δ1) Sin[θ14] (-Cos[θ35] Sin[θ24] Sin[θ25] Sin[θ45] + Cos[θ24] (Cos[θ34] Cos[θ45] - Sin[θ34] Sin[θ35] Sin[θ45]))) -
     e^(i δ0) Sin[θ13] (Cos[θ23] (-Cos[θ45] Sin[θ34] - Cos[θ34] Sin[θ35] Sin[θ45]) + Sin[θ23] (-Cos[θ24] Cos[θ35] Sin[θ25] Sin[θ45] - Sin[θ24] (Cos[θ34] Cos[θ45] - Sin[θ34] Sin[θ35] Sin[θ45])))),
  e^(-i δ0) (Sin[θ13] (-e^(i δ2) Cos[θ14] Cos[θ25] Cos[θ35] Sin[θ15] Sin[θ45] - e^(i δ1) Sin[θ14] (-Cos[θ35] Sin[θ24] Sin[θ25] Sin[θ45] + Cos[θ24] (Cos[θ34] Cos[θ45] - Sin[θ34] Sin[θ35] Sin[θ45]))) +
    e^(i δ0) Cos[θ13] (Cos[θ23] (-Cos[θ45] Sin[θ34] - Cos[θ34] Sin[θ35] Sin[θ45]) + Sin[θ23] (-Cos[θ24] Cos[θ35] Sin[θ25] Sin[θ45] - Sin[θ24] (Cos[θ34] Cos[θ45] - Sin[θ34] Sin[θ35] Sin[θ45])))),
  e^(-i δ1) (-e^(i δ2) Cos[θ25] Cos[θ35] Sin[θ14] Sin[θ15] Sin[θ45] + e^(i δ1) Cos[θ14] (-Cos[θ35] Sin[θ24] Sin[θ25] Sin[θ45] + Cos[θ24] (Cos[θ34] Cos[θ45] - Sin[θ34] Sin[θ35] Sin[θ45]))), Cos[θ15] Cos[θ25] Cos[θ35] Sin[θ45]},
 {-Sin[θ12] (-Sin[θ23] (-Cos[θ34] Cos[θ45] Sin[θ35] + Sin[θ34] Sin[θ45]) + Cos[θ23] (-Cos[θ24] Cos[θ35] Cos[θ45] Sin[θ25] - Sin[θ24] (-Cos[θ45] Sin[θ34] Sin[θ35] - Cos[θ34] Sin[θ45]))) +
   Cos[θ12] (Cos[θ13] (-e^(i δ2) Cos[θ14] Cos[θ25] Cos[θ35] Cos[θ45] Sin[θ15] - e^(i δ1) Sin[θ14] (-Cos[θ35] Cos[θ45] Sin[θ24] Sin[θ25] + Cos[θ24] (-Cos[θ45] Sin[θ34] Sin[θ35] - Cos[θ34] Sin[θ45]))) -
     e^(i δ0) Sin[θ13] (Cos[θ23] (-Cos[θ34] Cos[θ45] Sin[θ35] + Sin[θ34] Sin[θ45]) + Sin[θ23] (-Cos[θ24] Cos[θ35] Cos[θ45] Sin[θ25] - Sin[θ24] (-Cos[θ45] Sin[θ34] Sin[θ35] - Cos[θ34] Sin[θ45])))),
  Cos[θ12] (-Sin[θ23] (-Cos[θ34] Cos[θ45] Sin[θ35] + Sin[θ34] Sin[θ45]) + Cos[θ23] (-Cos[θ24] Cos[θ35] Cos[θ45] Sin[θ25] - Sin[θ24] (-Cos[θ45] Sin[θ34] Sin[θ35] - Cos[θ34] Sin[θ45]))) +
   Sin[θ12] (Cos[θ13] (-e^(i δ2) Cos[θ14] Cos[θ25] Cos[θ35] Cos[θ45] Sin[θ15] - e^(i δ1) Sin[θ14] (-Cos[θ35] Cos[θ45] Sin[θ24] Sin[θ25] + Cos[θ24] (-Cos[θ45] Sin[θ34] Sin[θ35] - Cos[θ34] Sin[θ45]))) -
     e^(i δ0) Sin[θ13] (Cos[θ23] (-Cos[θ34] Cos[θ45] Sin[θ35] + Sin[θ34] Sin[θ45]) + Sin[θ23] (-Cos[θ24] Cos[θ35] Cos[θ45] Sin[θ25] - Sin[θ24] (-Cos[θ45] Sin[θ34] Sin[θ35] - Cos[θ34] Sin[θ45])))),
  e^(-i δ0) (Sin[θ13] (-e^(i δ2) Cos[θ14] Cos[θ25] Cos[θ35] Cos[θ45] Sin[θ15] - e^(i δ1) Sin[θ14] (-Cos[θ35] Cos[θ45] Sin[θ24] Sin[θ25] + Cos[θ24] (-Cos[θ45] Sin[θ34] Sin[θ35] - Cos[θ34] Sin[θ45]))) +
    e^(i δ0) Cos[θ13] (Cos[θ23] (-Cos[θ34] Cos[θ45] Sin[θ35] + Sin[θ34] Sin[θ45]) + Sin[θ23] (-Cos[θ24] Cos[θ35] Cos[θ45] Sin[θ25] - Sin[θ24] (-Cos[θ45] Sin[θ34] Sin[θ35] - Cos[θ34] Sin[θ45])))),
  e^(-i δ1) (-e^(i δ2) Cos[θ25] Cos[θ35] Cos[θ45] Sin[θ14] Sin[θ15] + e^(i δ1) Cos[θ14] (-Cos[θ35] Cos[θ45] Sin[θ24] Sin[θ25] + Cos[θ24] (-Cos[θ45] Sin[θ34] Sin[θ35] - Cos[θ34] Sin[θ45]))), Cos[θ15] Cos[θ25] Cos[θ35] Cos[θ45]}}
```

Neutrino oscillations with more than 3 flavours

Theoretical challenge: complicated dependence of observable oscillation probabilities on the fundamental parameters of the theory

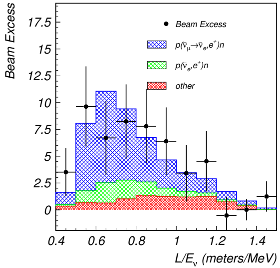
Analysis strategy

- Understand oscillation probabilities analytically
- Determine relevant parameters / parameter combinations for each experiment
- Use theoretical knowledge to simplify computations
- Perform global fit

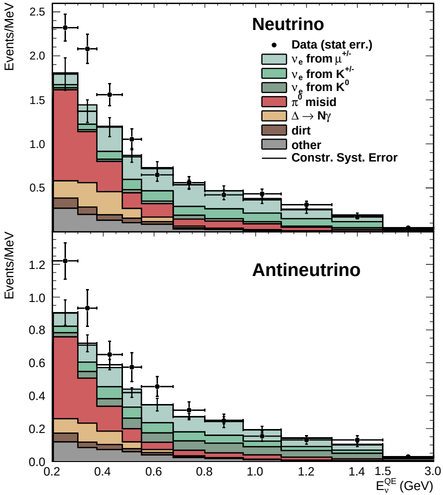
Giunti Laveder Archidiacono Fornengo Hannestad Melchiori Li Liu Long
Conrad Ignarra Karagiorgi Shaevitz Spitz Djurcic Sorel
JK Machado Maltoni Schwetz (this talk)

Oscillation anomalies: LSND and MiniBooNE

- LSND:
  - $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam from stopped pion source ($> 3\sigma$)
- MiniBooNE:
  - No significant ν_e or $\bar{\nu}_e$ excess in the LSND-preferred region
  - but $\bar{\nu}_e$ consistent with LSND
  - Low-E excess not understood



LSND hep-ex/0104049

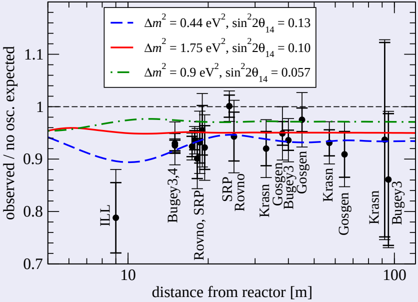


MiniBooNE arXiv:1207.4809

Reactor and gallium experiments

- Recent reevaluation of expected reactor $\bar{\nu}_e$ flux is $\sim$ 3.5% higher than previous prediction
  Mueller et al. arXiv:1101.2663, P. Huber arXiv:1106.0687
- Method: Use measured β-spectra from ^{238}U, ^{235}U, ^{241}Pu fission at ILL and convert to $\bar{\nu}_e$ spectrum (for single β-decay: $E_\nu = Q - E_e$)
- Requires knowledge of Q-values for all contributing decays.
  $\rightarrow$ take from nuclear databases where available, fit to data otherwise

see talks by Michel Cribier and Patrick Huber



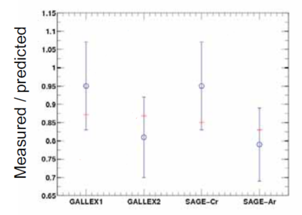
Reactor and gallium experiments

- Recent reevaluation of expected reactor $\bar{\nu}_e$ flux is $\sim 3.5\%$ higher than previous prediction
  Mueller et al. arXiv:1101.2663, P. Huber arXiv:1106.0687
- Method: Use measured β-spectra from ^{238}U, ^{235}U, ^{241}Pu fission at ILL and convert to $\bar{\nu}_e$ spectrum (for single β-decay: $E_\nu = Q - E_e$)
- Requires knowledge of Q-values for all contributing decays.
  $\rightarrow$ take from nuclear databases where available, fit to data otherwise

see talks by Michel Cribier and Patrick Huber

- Experiments with intense radioactive ν_e sources (^{51}Cr and ^{37}Ar)
- Neutrino detection via
  $^{71}\text{Ga} + \nu_e \rightarrow {}^{71}\text{Ge} + e^-$
- Observation: Neutrino deficit ($\sim 3\sigma$)

Giunti Laveder 1006.3244



Outline

1. Theoretical Motivation
2. Sterile Neutrino Oscillations: The Global Picture
3. Sterile Neutrinos in Cosmology
4. Conclusions

Data sets included in our fit

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

- SBL reactor experiments
- LBL reactor experiments
- KamLAND
- Radioactive source (Ga) experiments
- Solar neutrinos
- Atmospheric neutrinos
- ν_e–^{12}C scattering in KARMEN, LSND

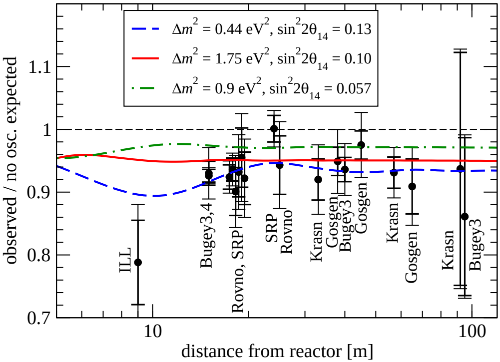
$\overset{(-)}{\nu}_e$ appearance

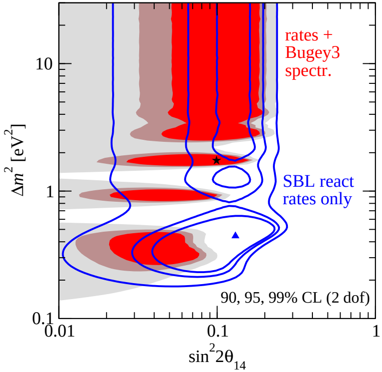
- LSND
- MiniBooNE
- KARMEN
- NOMAD
- ICARUS
- E776

$\overset{(-)}{\nu}_\mu$ disappearance

- Atmospheric neutrinos (includes *either* $\overset{(-)}{\nu}_e$ disapp. *or* full matter effects)
- MiniBooNE (includes oscillations of backgrounds)
- MINOS CC+NC (full n-flavour oscillations in matter)
- CDHS

$\overset{(-)}{\nu}_e$ disappearance in the 3+1 scenario

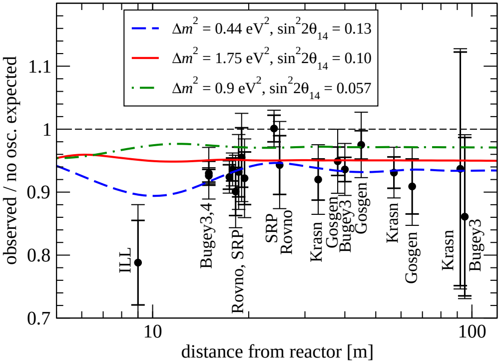


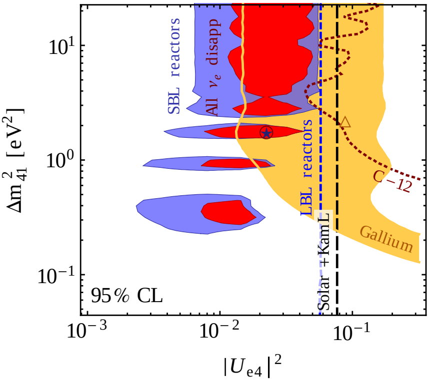


	$\sin^2 2\theta_{14}$	Δm^2_{41} [eV^2]	χ^2_{min}/dof (GOF)	$\Delta\chi^2_{no\ osc}$/dof (CL)
SBL rates only	0.13	0.44	11.5/17 (83%)	11.4/2 (99.7%)
SBL incl. Bugey3 spect.	0.10	1.75	58.3/74 (91%)	9.0/2 (98.9%)

JK Machado Maltoni Schwetz, in preparation

$\overset{(-)}{\nu}_e$ disappearance in the 3+1 scenario

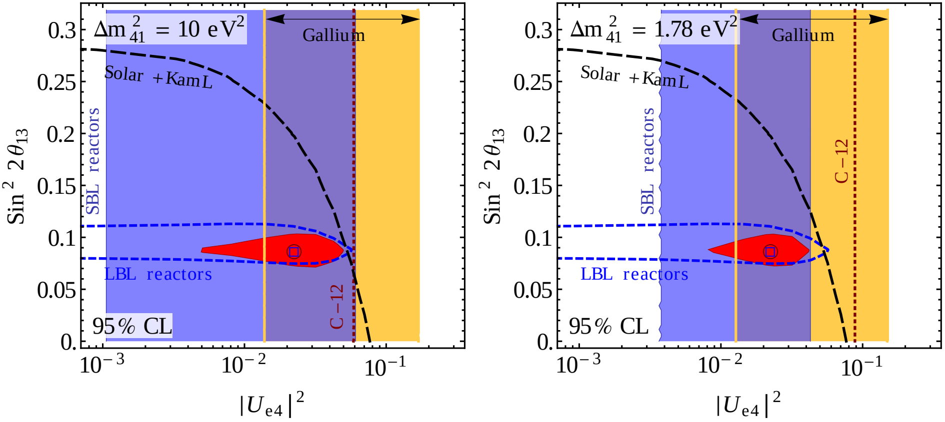




	$\sin^2 2\theta_{14}$	Δm^2_{41} [eV^2]	χ^2_{min}/dof (GOF)	$\Delta\chi^2_{no\ osc}$/dof (CL)
SBL rates only	0.13	0.44	11.5/17 (83%)	11.4/2 (99.7%)
SBL incl. Bugey3 spect.	0.10	1.75	58.3/74 (91%)	9.0/2 (98.9%)
SBL + Gallium	0.11	1.80	64.0/78 (87%)	14.0/2 (99.9%)
global ν_e disapp.	0.09	1.78	403.3/427 (79%)	12.6/2 (99.8%)

JK Machado Maltoni Schwetz, in preparation

Impact of θ_{13}

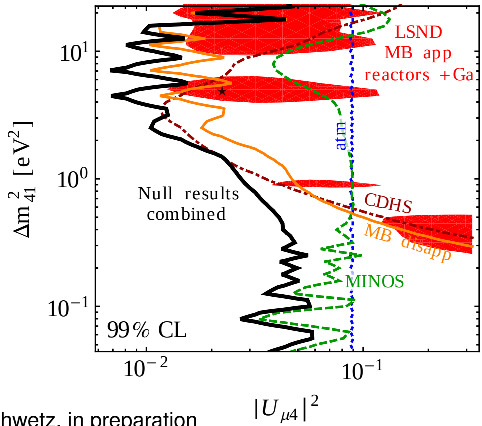


- Sterile neutrinos do not impact θ_{13} measurement
- $\theta_{13} \neq 0$ does not impact sterile neutrino search

JK Machado Maltoni Schwetz, in preparation

$\overset{(-)}{\nu}_\mu$ disappaearance in the 3+1 scenario

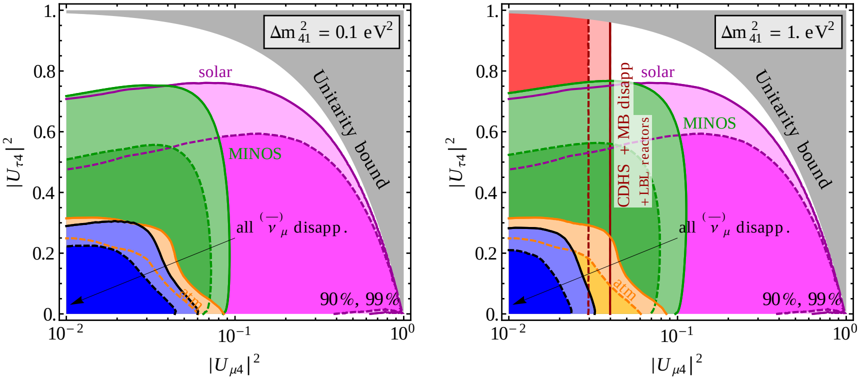
- Parameter regions favored by tentative hints are in tension with null results



JK Machado Maltoni Schwetz, in preparation

$\overset{(-)}{\nu}_\mu$ disappaearance in the 3+1 scenario

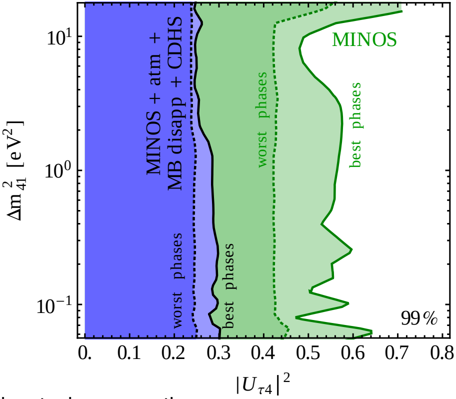
- Parameter regions favored by tentative hints are in tension with null results
- Constraints on $|U_{\tau 4}| \sim \sin\theta_{34}$ possible due to NC events and matter effects



JK Machado Maltoni Schwetz, in preparation

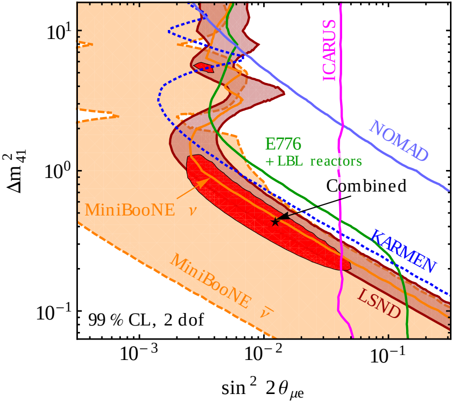
$\overset{(-)}{\nu}_\mu$ disappaearance in the 3+1 scenario

- Parameter regions favored by tentative hints are in tension with null results
- Constraints on $|U_{\tau 4}| \sim \sin\theta_{34}$ possible due to NC events and matter effects
- Complex phases important

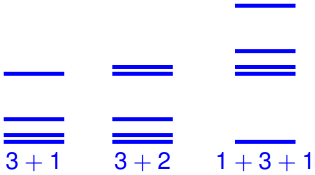


JK Machado Maltoni Schwetz, in preparation

$\overset{(-)}{\nu}_e$ appearance in the 3+1 scenario and beyond



	χ^2_{3+1}/dof	χ^2_{3+2}/dof	χ^2_{1+3+1}/dof
LSND	11.0/11	8.6/11	7.5/11
MiniB ν	19.3/11	10.6/11	9.1/11
MiniB $\bar{\nu}$	10.7/11	9.6/11	12.7/11
E776	32.4/24	29.2/24	31.3/24
KARMEN	9.8/9	8.6/9	9.0/9
NOMAD	0.0/1	0.0/1	0.0/1
ICARUS	2.0/1	2.3/1	1.5/1
Combined	87.9/66	72.7/63	74.6/63

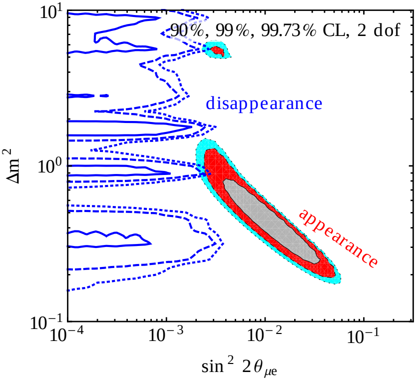


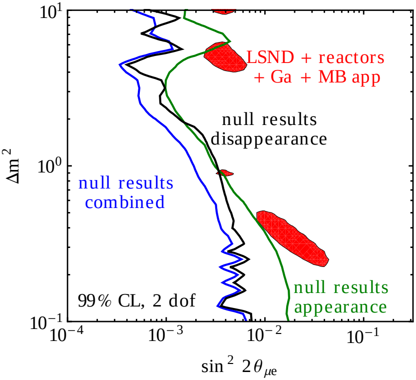
- Global fit to all appearance data is consistent
- Background oscillations important in MiniBooNE and E776
- Significant improvement in $3+2$ and $1+3+1$

JK Machado Maltoni Schwetz, in preparation

The global oscillation fit

JK Machado Maltoni Schwetz, in preparation



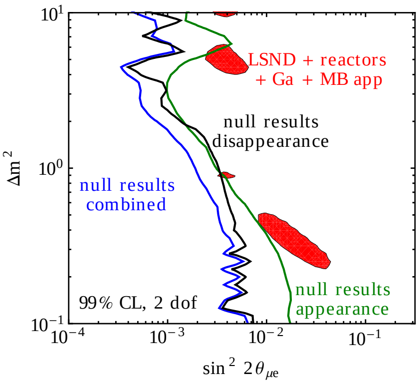


	χ^2_{min}/dof	GOF
3+1	712/(689 − 9)	19%

The global oscillation fit

JK Machado Maltoni Schwetz, in preparation

3 + 1 Severe tension between appearance and disappearance and between exp's with and without a signal

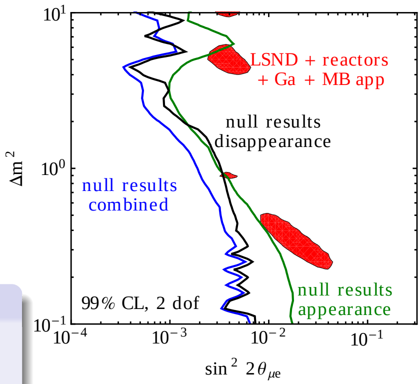


	χ^2_{min}/dof	GOF
3+1	712/(689 – 9)	19%

The global oscillation fit

JK Machado Maltoni Schwetz, in preparation

$3+1$ Severe tension between appearance and disappearance and between exp's with and without a signal



Parameter goodness of fit (PG) test:

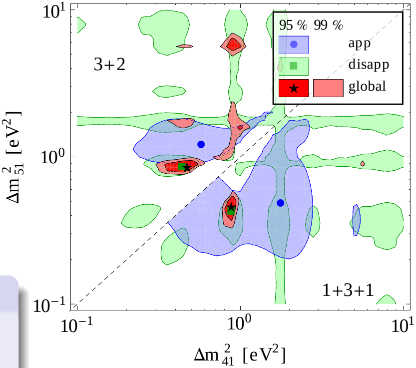
Compares χ^2_{min} from global and separate fits to test compatibility of 2 data sets

	χ^2_{min}/dof	GOF	χ^2_{PG}/dof	PG
3+1	712/(689 − 9)	19%	18.0/2	1.2×10^{-4}

The global oscillation fit

JK Machado Maltoni Schwetz, in preparation

- $3+1$ Severe tension between appearance and disappearance and between exp's with and without a signal
- $3+2$ Fit improves considerably with two sterile neutrinos



Parameter goodness of fit (PG) test:

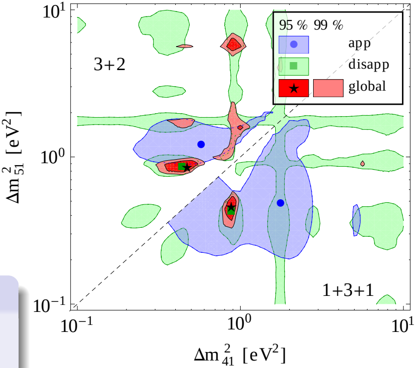
Compares χ^2_{min} from global and separate fits to test compatibility of 2 data sets

	χ^2_{min}/dof	GOF	χ^2_{PG}/dof	PG
3+1	712/(689 − 9)	19%	18.0/2	1.2×10^{-4}
3+2	701/(689 − 14)	23%	25.8/4	3.4×10^{-5}

The global oscillation fit

JK Machado Maltoni Schwetz, in preparation

- $3+1$ Severe tension between appearance and disappearance and between exp's with and without a signal
- $3+2$ Fit improves considerably with two sterile neutrinos
- $1+3+1$ Further improvement, especially in appearance fit



Parameter goodness of fit (PG) test:

Compares χ^2_{min} from global and separate fits to test compatibility of 2 data sets

	χ^2_{min}/dof	GOF	χ^2_{PG}/dof	PG
3+1	712/(689 − 9)	19%	18.0/2	1.2×10^{-4}
3+2	701/(689 − 14)	23%	25.8/4	3.4×10^{-5}
1+3+1	694/(689 − 14)	30%	16.8/4	2.1×10^{-3}

Conclusion from oscillation fits:

severe tension

in all cases

Outline

1 Theoretical Motivation

2 Sterile Neutrino Oscillations: The Global Picture

3 Sterile Neutrinos in Cosmology

4 Conclusions

Sterile neutrinos in cosmology

Models with $\mathcal{O}$(eV) sterile neutrino(s) constrained by cosmology:

Sum of neutrino masses

$$\sum m_\nu \lesssim 0.5\text{ eV}$$

# of relativistic species

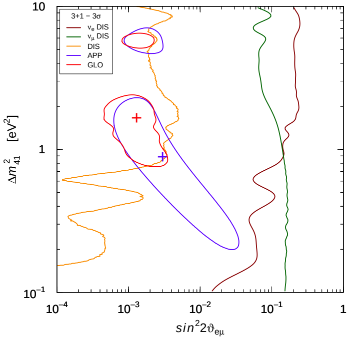
$N_\nu > 3$ mildly preferred

see e.g. Hinshaw et al. (WMAP-9), arXiv:1212.5226
Gonzalez-Garcia Maltoni Salvado, arXiv:1006.3795
Hamann Hannestad Raffelt Tamborra Wong, arXiv:1006:5276

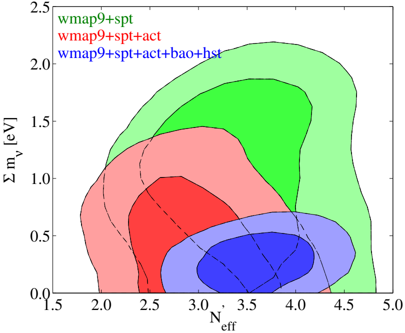
Ways out:

- Large lepton asymmetry ($\gtrsim 0.01$) → suppressed production
  Foot Volkas hep-ph/9508275 Chu Cirelli, astro-ph/0608206 Saviano et al., arXiv:1302.1200
- > 1 new relativistic degrees of freedom + $w < -1$ + $\mu_\nu \neq 0$
  Hamann Hannestad Raffelt Wong, arXiv:1108.4136
- Couplings to a Majoron field → suppressed production
  Bento Berezhiani, hep-ph/0108064

A combined fit of oscillation data and cosmology

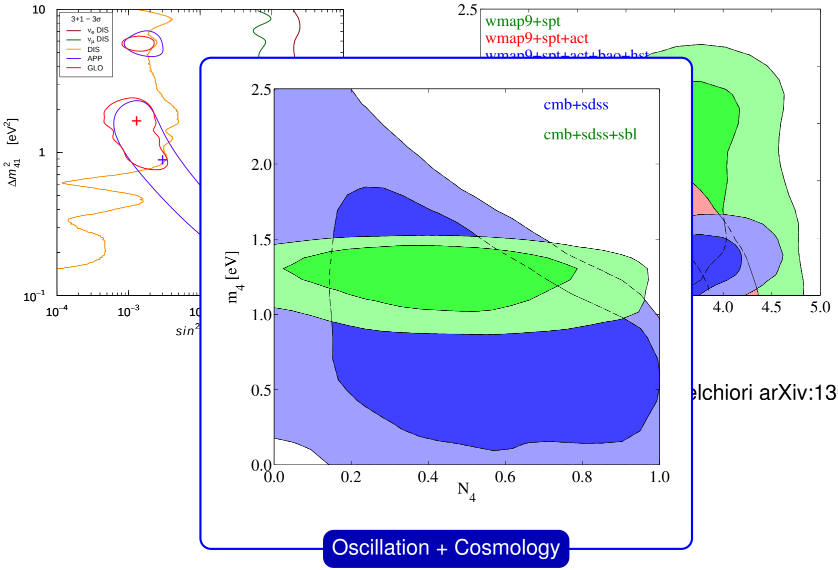


+



Archidiacono Fornengo Giunti Hannestad Melchiori arXiv:1302.6720

A combined fit of oscillation data and cosmology



elchiori arXiv:1302.6720

Outline

1. Theoretical Motivation
2. Sterile Neutrino Oscillations: The Global Picture
3. Sterile Neutrinos in Cosmology
4. Conclusions

Summary

- Sterile neutrinos are theoretically well motivated and phenomenologically useful
- Global fits shows severe tension between appearance and disappearance searches
  - Note: Different groups come to somewhat different conclusions
- Cosmological bounds strong, but can be avoided in several ways

Are there eV-scale sterile neutrinos? — Conclusions

Substantial tension in the global fit.

- Is one (or all) of the positive results not due to neutrino oscillations?
- Are some of the null results wrong?

  (one being wrong is not enough!)
- Are there more than 2 sterile flavors?
- Are there sterile neutrinos plus something else?

The answer to these questions is a definite

“we don’t know . . . yet”

Thank you!

Relation between appearance and disappearance

$3 + 1$ neutrinos

At large baseline ($L \gg 4\pi E/\Delta m^2_{41}$, but $L \ll 4\pi E/\Delta m^2_{31}$

$$P_{ee} = 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$
$$P_{\mu\mu} = 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$
$$P_{e\mu} = 2|U_{e4}|^2|U_{\mu 4}|^2$$

It follows

$$2P_{e\mu} \simeq (1 - P_{ee})(1 - P_{\mu\mu})$$

In the $3 + 1$ case, at large enough baseline, there is a one-to-one relation between the appearance and disappearance probabilities.

Relation between appearance and disappearance

$3 + 2$ neutrinos

At large baseline ($L \gg 4\pi E/\Delta m^2_{41}$, but $L \ll 4\pi E/\Delta m^2_{31}$

$$P_{ee} = 1 - 2\Big[|U_{e4}|^2(1 - |U_{e4}|^2) + |U_{e5}|^2(1 - |U_{e5}|^2) - |U_{e4}|^2|U_{e5}|^2\Big]$$

$$P_{\mu\mu} = 1 - 2\Big[|U_{\mu4}|^2(1 - |U_{\mu4}|^2) + |U_{\mu5}|^2(1 - |U_{\mu5}|^2) - |U_{\mu4}|^2|U_{\mu5}|^2\Big]$$

$$P_{e\mu} = 2\Big[|U_{e4}|^2|U_{\mu4}|^2 + |U_{\mu4}|^2|U_{\mu5}|^2 + \mathrm{Re}(U^*_{e4}U_{\mu4}U_{e5}U^*_{\mu5})\Big]$$

Relation between appearance and disappearance

$3 + 2$ neutrinos

At large baseline ($L \gg 4\pi E/\Delta m^2_{41}$, but $L \ll 4\pi E/\Delta m^2_{31}$

$$P_{ee} = 1 - 2\Big[|U_{e4}|^2(1 - |U_{e4}|^2) + |U_{e5}|^2(1 - |U_{e5}|^2) - |U_{e4}|^2|U_{e5}|^2\Big]$$

$$P_{\mu\mu} = 1 - 2\Big[|U_{\mu4}|^2(1 - |U_{\mu4}|^2) + |U_{\mu5}|^2(1 - |U_{\mu5}|^2) - |U_{\mu4}|^2|U_{\mu5}|^2\Big]$$

$$P_{e\mu} = 2\Big[|U_{e4}|^2|U_{\mu4}|^2 + |U_{\mu4}|^2|U_{\mu5}|^2 + \mathrm{Re}(U^*_{e4}U_{\mu4}U_{e5}U^*_{\mu5})\Big]$$

It follows

$$\begin{aligned}
2P_{e\mu} &\simeq (1 - P_{ee})(1 - P_{\mu\mu}) \\
&\quad + 4\Big[\mathrm{Re}(U^*_{e4}U_{\mu4}U_{e5}U^*_{\mu5}) + 4|U_{e4}|^2|U_{\mu5}|^2 + 4|U_{e5}|^2|U_{\mu4}|^2\Big] \\
&= (1 - P_{ee})(1 - P_{\mu\mu}) - 2\Big[|U_{e4}|^2|U_{\mu5}|^2 + |U_{e5}|^2|U_{\mu4}|^2\Big] \\
&\quad - 2\big|U_{e4}U_{\mu5} - U_{e5}U_{\mu4}\big|^2
\end{aligned}$$

Relation between appearance and disappearance

$3 + 2$ neutrinos

At large baseline ($L \gg 4\pi E/\Delta m^2_{41}$, but $L \ll 4\pi E/\Delta m^2_{31}$

$$P_{ee} = 1 - 2\Big[|U_{e4}|^2(1 - |U_{e4}|^2) + |U_{e5}|^2(1 - |U_{e5}|^2) - |U_{e4}|^2|U_{e5}|^2\Big]$$

$$P_{\mu\mu} = 1 - 2\Big[|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) + |U_{\mu 5}|^2(1 - |U_{\mu 5}|^2) - |U_{\mu 4}|^2|U_{\mu 5}|^2\Big]$$

$$P_{e\mu} = 2\Big[|U_{e4}|^2|U_{\mu 4}|^2 + |U_{\mu 4}|^2|U_{\mu 5}|^2 + \mathrm{Re}(U^*_{e4}U_{\mu 4}U_{e5}U^*_{\mu 5})\Big]$$

It follows

$$2P_{e\mu} \leq (1 - P_{ee})(1 - P_{\mu\mu})$$

Unlike in the $3 + 1$ case, for $3 + 2$ models, there is NO one-to-one relation between the appearance and disappearance probabilities.

However, there is an inequality, which can be used to set meaningful constraints.

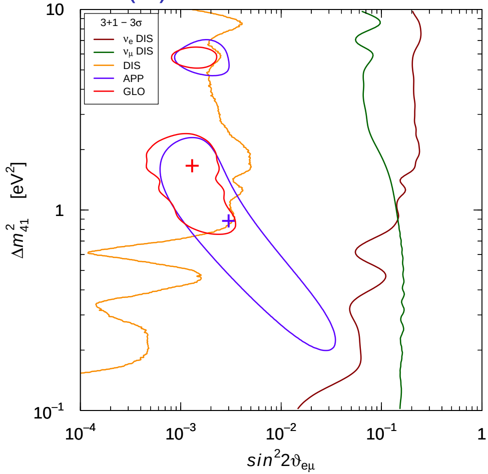
The Giunti et al. fit

Includes the following data sets:

- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance data:
  - LSND
  - MiniBooNE ($E > 475$ MeV)
  - KARMEN
  - NOMAD
  - ICARUS
- $\overset{(-)}{\nu}_\mu$ disappearance data:
  - CDHS
  - MINOS bound on $|U_{\mu 4}|$
- $\overset{(-)}{\nu}_e$ disappearance data:
  - Reactor experiments
  - Gallium anomaly
  - Solar neutrinos
  - KamLAND
  - ν_e–^{12}C CC scattering in KARMEN and LSND

Archidiacono Fornengo Giunti Hannestad Melchiori arXiv:1302.6720
see also Giunti Laveder Li Liu Long arXiv:1210.5715
Giunti Laveder arXiv:1111.1069

The Giunti et al. fit (2)



APP/DIS curves: 3σ C.L.

Parameter goodness of fit (APP vs. DIS): 4%

Archidiacono Fornengo Giunti Hannestad Melchiori arXiv:1302.6720
see also Giunti Laveder Li Liu Long arXiv:1210.5715
Giunti Laveder arXiv:1111.1069

Differences between our fit and Giunti et al.

- MiniBooNE fit
  we use MB analysis based on official MC events, include BG oscillation
- MINOS fit
  we fit CC+NC data, including ND and FD, detector response matrices based on official MINOS MC
- Reactor fit
  minor differences in the data set, possibly different treatment of correlations among systematic uncertainties
- LSND fit
  Note that LSND spectral data is more constraining than the total count rate. We use this information; our fit is consistent with the numbers reported in hep-ex/0203023 (Church, Eitel, Mills, Steidl, combined LSND+KARMEN analysis)
- Atmospheric neutrinos
  Full fit vs. tabulated χ^2

The Karagiorgi et al. fit

Conrad Ignarra Karagiorgi Shaevitz Spitz arXiv:1207.4765

Karagiorgi arXiv:1110.3735

Karagiorgi Djurcic Conrad Shaevitz Sorel arXiv:0906.1997

Includes the following data sets:

- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance data:
  - LSND
  - MiniBooNE
  - KARMEN
  - NOMAD
- $\overset{(-)}{\nu}_\mu$ disappearance data:
  - MiniBooNE
  - Minos CC u_μ
  - CDHS
  - CCFR
  - Atmospheric neutrinos
- $\overset{(-)}{\nu}_e$ disappearance data:
  - Short baseline reactor experiments
  - Gallium experiments
  - ν_e–^{12}C CC scattering in KARMEN and LSND

Result

χ^2/dof and PG test results in qualitative agreement with ours