Fitting the short-baseline anomalies

Joachim Kopp

The 4th neutrino – U Chicago, May 19, 2012

Fermilab
Outline

1. Sterile neutrinos
2. Data sets and fitting procedure
3. Fit results
4. Relation between appearance and disappearance
5. Conclusions
Theoretical motivation for sterile neutrinos

- **Standard Model singlet** fermions are a very generic feature of “new physics” models
  - Leftovers of extended gauge multiplets (e.g. GUT multiplets) (typically heavy)
  - Dark matter (keV ... TeV or above)

- **Neutrino–singlet mixing** is one of the allowed “portals” between the SM and a hidden sector.

- **SM singlet fermions can live at any mass scale**
  - Here: Focus on $\mathcal{O}(\text{eV})$ sterile neutrinos (accessible to oscillation experiments)
  - Motivated experimentally

- **Typical Lagrangian:**

\[
\mathcal{L}_{\text{mass}} \supset Y_{\nu} \bar{L} H^* N_R + m_s \bar{\nu}_s N_R + \frac{1}{2} M \overline{N^c_R} N_R + h.c.
\]

⇒ mass mixing between active and sterile neutrinos
Signatures in oscillation experiments

- Disappearance of active neutrinos (e.g. $\nu_e \rightarrow \nu_s$ oscillations)
- Anomalous transitions Appearance among active neutrinos (e.g. $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$)

Oscillation length $L_{\text{osc}} = \frac{4\pi E}{\Delta m_{41}^2}$ different from SM expectation (typically shorter)

Notation: $\Delta m_{jk}^2 = m_j^2 - m_k^2$; $m_{4,5}$: mostly sterile, $m_{1,2,3}$: mostly active
Sterile neutrino oscillations

Idea:

- Introduce extra neutrino flavor $\nu_s$, mixing with the active ones
- **Appearance searches** (KARMEN, NOMAD, MiniBooNE . . . ) constrain $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e, \nu_\tau$
- **Disappearance searches** (reactors, CDHS, MINOS . . . ) constrain $\nu_e, \nu_\mu \rightarrow \bar{\nu}_s$
- $\bar{\nu}_e \rightarrow \bar{\nu}_s$ oscillations explain reactor anomaly
- $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$ oscillations explain LSND + MiniBooNE $\bar{\nu}$
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Our fitting procedure

- **Atmospheric neutrinos:** Eight classes of events: Sub-GeV $e, \mu$ ($p < 400$ GeV/c), Sub-GeV $e, \mu$ ($p > 400$ GeV/c), Multi-GeV $e, \mu$, Upward stopping $\mu$, upward throughgoing $\mu$, 10 zenith angle bins each

- **MINOS:** Include NC and CC disappearance search
  (based on 1001.0336 and Neutrino 2010 talk by P. Vahle)

- **Reactor experiments:** 
  - Bugey 3 (incl. spectrum), Bugey 4, Chooz (incl. spectrum),
  - Goesgen 1–3, ILL, Krasnoyarsk 1–3, Palo Verde, Rovno

- **SBL $\nu_e$ appearance experiments:** 
  - LSND, KARMEN, MiniBooNE ($\nu$ (2010) and $\bar{\nu}$ data, consider only $E > 475$ MeV, i.e. low-$E$ excess in $\nu_e$ sample not included)

- **Gallium anomaly** not included

- **SBL $\nu_\mu$ disappearance experiments:** CDHS, NOMAD

- **All codes reproduce the individual fits** from the respective experiments.

JK Maltoni Schwetz 1103.4570 and work in progress


LSND and MiniBooNE

- **LSND:**
  - $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam from stopped pion source ($3\sigma$)

- **MiniBooNE:**
  - No significant $\nu_e$ or $\bar{\nu}_e$ excess in the LSND-preferred region
  - but $\bar{\nu}_e$ consistent with LSND
  - Low-\(E\) excess not understood

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![Graph showing beam excess and LSND $\bar{\nu}_e$](image1)

![Graph showing MiniBooNE $\nu_e$ and $\bar{\nu}_e$](image2)
The reactor anomaly

- **Recent reevaluation** of expected reactor $\bar{\nu}_e$ flux is $\sim 3.5\%$ higher than previous prediction. Mueller et al. arXiv:1101.2663, confirmed by P. Huber arXiv:1106.0687

- **Method**: Use measured $\beta$-spectra from $^{238}U$, $^{235}U$, $^{241}Pu$ fission at ILL and convert to $\bar{\nu}_e$ spectrum (for single $\beta$-decay: $E_\nu = Q - E_e$)

- **Problem**: Requires knowledge of $Q$-values for all contributing decays. → take from nuclear databases where available, fit to data otherwise

- **Cross check**:
  - Simulate **mock $e^-$ spectra** using few well-understood $\beta$-decays
  - Reconstruct $\bar{\nu}_e$ spectrum using **old method**: Result is $3\%$ too low
  - Reconstruct $\bar{\nu}_e$ spectrum using **new method**: Result is exact.

- **Possible problem**: Poorly understood effects in nuclei with large log $ft$. Huber arXiv:1106.0687
The reactor anomaly

- Have short-baseline reactor experiments observed a $\bar{\nu}_e$ deficit?

![Graph showing short-baseline reactor anomaly data](image)

**red** = old reactor $\bar{\nu}_e$ flux prediction

**blue** = new reactor $\bar{\nu}_e$ flux prediction

Mention et al. arXiv:1101.2755
MINOS NC disappearance search

- Based on arXiv:1001.0336 and data shown at Neutrino 2010
- GLoBES simulation
- NC data:
  - Use spectra and detector response functions based on MINOS MC (courtesy Alex Sousa)
- CC data:
  - NuMI fluxes courtesy Mary Bishai
  - Backgrounds and efficiencies based on published results
- Systematic uncertainties:
  - Based on published numbers, but simplified treatment
  - Some fudging in CC channel
MINOS NC disappearance search (2)

Near detector NC

Far detector NC

Near detector CC

Far detector CC

Events / GeV

$E_{\text{reco}}$ [GeV]

Fitting the short-baseline anomalies

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MINOS NC disappearance search (3)

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Fitting the short-baseline anomalies
A 3+1 model: 3 active neutrinos + 1 sterile neutrino

- Short baseline: Standard oscillations ineffective ($\Delta m_{21}^2$, $\Delta m_{31}^2$ too small)
- Add extra (sterile) neutrino
- Fit shows: 3+1 neutrino scheme does not work well

JK Maltoni Schwetz 1103.4570 and work in progress
see also Giunti Laveder 1107.1452 and 1109.4033; Mention et al. 1101.2755; Karagiorgi et al. 0906.1997 and 1110.3735

"disappearance" = SBL reactors, CDHS, atmospheric $\nu$, MINOS
$\theta$ = effective mixing angle for $\overline{\nu}_\mu \rightarrow \overline{\nu}_s \rightarrow \overline{\nu}_e$ oscillations
Global fit in a 4-flavor scheme

| $|\Delta m_{41}^2|$ | $|U_{e4}|$ | $|U_{\mu4}|$ | $\chi^2$/dof |
|-----------------|---------|---------|-------------|
| STD             |         |         |             |
| 3+1             | 0.48    | 0.14    | 0.23        | 287.6/256   |
|                 |         |         |             |
| LSND+MB($\bar{\nu}$) vs rest | appearance vs disapp. |
| old             | new     | old     | new         |
| $\chi^2_{PG,3+1}$/dof | 27.3/2 | 25.8/2  | 15.7/2      | 14.2/2      |
| $PG_{3+1}$      | $1.2 \times 10^{-6}$ | $2.5 \times 10^{-6}$ | $3.9 \times 10^{-4}$ | $8.2 \times 10^{-4}$ |

Parameter goodness of fit: Test compatibility of 2 data sets by comparing global $\chi^2_{\text{min}}$ to $\chi^2_{\text{min}}$ for separate fits.
The Giunti–Laveder fit

Includes the following data sets:

- $\nu_\mu \rightarrow \nu_e$ appearance data:
  - LSND
  - MiniBooNE
  - KARMEN
  - NOMAD

- $\nu_\mu$ disappearance data:
  - CDHS
  - MINOS bound on $|U_{\mu4}|$

- $\bar{\nu}_e$ disappearance data:
  - Short baseline reactor experiments
  - KamLAND bound on $|U_{e4}|$
  - Gallium anomaly

- $\nu_e$ disappearance data:
  - $\nu_e-^{12}C$ CC scattering in KARMEN and LSND

Giunti Laveder arXiv:1111.1069
The Giunti–Laveder fit (2)

APP/DIS curves: \(3\sigma\) C.L.
Parameter goodness of fit (APP vs. DIS): \(3 \times 10^{-3}\)

Giunti Laveder arXiv:1111.1069
The Karagiorgi et al. fit

Includes the following data sets:

- \( \overline{\nu}_\mu \rightarrow \overline{\nu}_e \) appearance data:
  - LSND
  - MiniBooNE
  - KARMEN
  - NOMAD

- \( \nu_\mu \) disappearance data:
  - CDHS
  - CCFR84

- \( \overline{\nu}_e \) disappearance data:
  - Short baseline reactor experiments

The Karagiorgi et al. fit (2)

Global fit in a 5-flavor scheme

Check if more than one sterile neutrino improves the fit:

\[ \Delta m_{41} [\text{eV}^2] \]

\[ \Delta m_{51} [\text{eV}^2] \]

90\%, 95\%, 99\%, 99.73\%

JK Maltoni Schwetz 1103.4570 and work in progress
Global fit in a 5-flavor scheme (2)

| Parameter | $|\Delta m_{41}^2|$ | $|U_e4|$ | $|U_\mu4|$ | $|\Delta m_{51}^2|$ | $|U_e5|$ | $|U_\mu5|$ | $\delta/\pi$ | $\chi^2$/dof |
|-----------|-----------------|--------|--------|-----------------|--------|--------|----------|-------------|
| STD       |                 |        |        |                 |        |        |          | 287.6/256   |
| 3+1       | 0.48            | 0.14   | 0.23   |                 |        |        | -0.31    | 255.5/252   |
| 3+2       | 1.10            | 0.14   | 0.11   | 0.82            | 0.13   | 0.12   | 0.14     | 245.2/247   |
| 1+3+1     | 0.48            | 0.13   | 0.12   | 0.90            | 0.15   | 0.15   | 0.62     | 241.6/247   |

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\chi^2$/dof</th>
<th>$\chi^2$/dof</th>
<th>$\chi^2$/dof</th>
<th>$\chi^2$/dof</th>
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<tbody>
<tr>
<td>$\chi_{PG,3+1}^2$/dof</td>
<td>27.3/2</td>
<td>25.8/2</td>
<td>15.7/2</td>
<td>14.2/2</td>
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<td>$PG_{3+1}$</td>
<td>$1.2 \times 10^{-6}$</td>
<td>$2.5 \times 10^{-6}$</td>
<td>$3.9 \times 10^{-4}$</td>
<td>$8.2 \times 10^{-4}$</td>
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<td>$\chi_{PG,3+2}^2$/dof</td>
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<td>$6.0 \times 10^{-3}$</td>
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Parameter goodness of fit: Test compatibility of 2 data sets by comparing global $\chi_{min}^2$ to $\chi_{min}^2$ for separate fits
Does removing *one* experiment relax the tension?

<table>
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<tr>
<th>Removing ...</th>
<th>LSND+MB($\bar{\nu}$) vs rest</th>
<th>appearance vs disapp.</th>
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<td>PG$_{3+1}$</td>
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<td>NOMAD</td>
<td>$2.6 \times 10^{-6}$</td>
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<td>Reactors</td>
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<td>CDHS</td>
<td>$1.2 \times 10^{-5}$</td>
<td>$3.7 \times 10^{-4}$</td>
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<tr>
<td>Atmospheric</td>
<td>$8.1 \times 10^{-6}$</td>
<td>$6.9 \times 10^{-5}$</td>
</tr>
<tr>
<td>MINOS</td>
<td>$1.4 \times 10^{-5}$</td>
<td>$1.1 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
Impact on standard oscillation parameters

Curves, circles: 3 flavors, atm + MINO
Colors, stars: 3+2 flavors, all exps

90%, 95%, 99%, 99.73%
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Relation between appearance and disappearance

3 + 1 neutrinos

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

\[
P_{ee} = 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)
\]
\[
P_{\mu\mu} = 1 - 2|U_{\mu4}|^2(1 - |U_{\mu4}|^2)
\]
\[
P_{e\mu} = 2|U_{e4}|^2|U_{\mu4}|^2
\]

It follows

\[
2P_{e\mu} \approx (1 - P_{ee})(1 - P_{\mu\mu})
\]

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 ($L \gg 4\pi E/\Delta m_{41}^2$, but $L \ll 4\pi E/\Delta m_{31}^2$)

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

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

\[
P_{e\mu} = 2 \left[ |U_{e4}|^2 |U_{\mu4}|^2 + |U_{\mu4}|^2 |U_{\mu5}|^2 + \text{Re}(U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*) \right]
\]
Relation between appearance and disappearance

3 + 2 neutrinos

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

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

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

\[
P_{e\mu} = 2 \left[ |U_{e4}|^2 |U_{\mu4}|^2 + |U_{\mu4}|^2 |U_{\mu5}|^2 + \text{Re}(U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*) \right]
\]

It follows

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

\[
+ 4 \left[ \text{Re}(U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*) + 4 |U_{e4}|^2 |U_{\mu5}|^2 + 4 |U_{e5}|^2 |U_{\mu4}|^2 \right]
\]

\[
= (1 - P_{ee})(1 - P_{\mu\mu}) - 2 \left[ |U_{e4}|^2 |U_{\mu5}|^2 + |U_{e5}|^2 |U_{\mu4}|^2 \right]
\]

\[
- 2 |U_{e4} U_{\mu5} - U_{e5} U_{\mu4}|^2
\]
Relation between appearance and disappearance

**3 + 2 neutrinos**

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

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

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

\[
P_{e\mu} = 2\left[|U_{e4}|^2|U_{\mu4}|^2 + |U_{\mu4}|^2|U_{\mu5}|^2 + \text{Re}(U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*)\right]
\]

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.
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Global fits — take home message

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?
Thank you!