Reactor anomaly, $\theta_{13}$, and sterile neutrinos
Neutrino Telescopes 2011

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16 March 2011
Outline

- The reactor anomaly
  refer to previous talk

- Implications for $\theta_{13}$
  TS, Tortola, Valle, 1103.0734

- Sterile neutrinos
  Kopp, Maltoni, TS, 1103.xxx

- Summary and outlook
The reactor anomaly

\[ \theta_{13} \]

Sterile neutrinos

Summary and outlook
New reactor anti-neutrino flux predictions

“new” fluxes Mueller et al., 1101.2663 compared to “old” fluxes Schreckenbach et al., 82, 85, 89

T. Schwetz (MPIK) Neutel Venice, 16 Mar 2011
are we seeing $\theta_{13}$, sterile neutrinos, or just a systematic error?
New reactor fluxes and SBL reactor data

still very good fit (within quoted uncertainties): P-value 37%

flux free analysis (dashed lines)
old flux best fit: $f = 0.984$ ($f = 1$ within $1\sigma$)
new flux best fit: $f = 0.942$ ($f = 1$: $\Delta\chi^2 = 6.2 \rightarrow 2.5\sigma$)

sterile neutrino with $\Delta m^2 \gtrsim 1 \text{ eV}^2$: $f \rightarrow \frac{1}{2} \sin^2 2\theta$
The reactor anomaly

New reactor fluxes and SBL reactor data

TS, Tortola, Valle, 11

\[ \chi^2 = 13.0 / 12 \]

\[ \chi^2 = 8.1 / 12 \]

- still very good fit (within quoted uncertainties): P-value 37%

- flux free analysis (dashed lines)
  old flux best fit: \( f = 0.984 \) (\( f = 1 \) within 1 \( \sigma \))
  new flux best fit: \( f = 0.942 \) (\( f = 1 \): \( \Delta \chi^2 = 6.2 \to 2.5 \sigma \))

- sterile neutrino with \( \Delta m^2 \gtrsim 1 \text{eV}^2 \): \( f \to \frac{1}{2} \sin^2 2\theta \)
Outline

The reactor anomaly

$\theta_{13}$

Sterile neutrinos

Summary and outlook
Reactor data and $\theta_{13}$

- using only CHOOZ and Palo Verde leads to a hint for $\theta_{13} > 0$ at $2\sigma$
- if SBL data are included the hint disappears and limits become similar with old and new fluxes
Solar and KamLAND data and $\theta_{13}$

- **KamLAND** prefers a non-zero $\theta_{13}$
- **solar + KamLAND + SBL** react:
  \[
  \sin^2 \theta_{13} = 0.030^{+0.015}_{-0.016}, \quad \Delta \chi^2(\sin^2 \theta_{13} = 0) = 4.4 \text{ (2.1}\sigma) 
  \]
  old fluxes:  \[
  \Delta \chi^2(\sin^2 \theta_{13} = 0) = 2.2
  \]
Atmospheric and MINOS data

- MINOS $\nu_\mu \rightarrow \nu_e$ appearance data: $(7 \times 10^{20} \text{ pot})$
  54 electron neutrino events, $49.1 \pm 7.0 \pm 2.7$ expected (0.7$\sigma$)
- SK I+II+II SK Coll, 1002.3471: $\Delta \chi^2(\sin^2 \theta_{13} = 0) = 0(0.3)$ for NH (IH)

T. Schwetz (MPIK)
Atmospheric and MINOS data

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- SK I+II+II SK Coll, 1002.3471: $\Delta\chi^2(\sin^2 \theta_{13} = 0) = 0(0.3)$ for NH (IH)
- but there is a $\sim 1\sigma$ hint from SK + MINOS combined:

\[
\Delta\chi^2(\theta_{13} = 0) = 1.6(1.9) \text{ for NH (IH)}
\]
Global data on $\theta_{13}$

<table>
<thead>
<tr>
<th></th>
<th>$\sin^2 \theta_{13}$</th>
<th>$\Delta \chi^2 (\theta_{13} = 0)$</th>
<th>$3\sigma$ bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH</td>
<td>$0.017^{+0.007}_{-0.009}$</td>
<td>$4.9 \ (2.2\sigma)$</td>
<td>$0.040$</td>
</tr>
<tr>
<td>IH</td>
<td>$0.020^{+0.008}_{-0.009}$</td>
<td>$5.4 \ (2.3\sigma)$</td>
<td>$0.044$</td>
</tr>
</tbody>
</table>
\( \theta_{13} \) depends on SBL reactor treatment

<table>
<thead>
<tr>
<th></th>
<th>( \sin^2 \theta_{13} )</th>
<th>( \Delta \chi^2(\theta_{13} = 0) )</th>
<th>3( \sigma ) bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>solar + KamLAND + SBL</td>
<td>0.030_{-0.016}^{+0.015}</td>
<td>4.4 (2.1( \sigma ))</td>
<td>0.079</td>
</tr>
<tr>
<td>Chooz + Palo Verde + SBL</td>
<td>0.009_{-0.011}^{+0.012}</td>
<td>0.7 (0.8( \sigma ))</td>
<td>0.044</td>
</tr>
<tr>
<td>atmospheric + MINOS</td>
<td>0.010_{-0.016}^{+0.016}</td>
<td>1.7 (1.3( \sigma ))</td>
<td>0.057</td>
</tr>
<tr>
<td></td>
<td>0.020_{-0.015}^{+0.018}</td>
<td>1.9 (1.4( \sigma ))</td>
<td>0.075</td>
</tr>
<tr>
<td>atmos + MINOS + solar</td>
<td>0.013_{-0.012}^{+0.014}</td>
<td>2.3 (1.5( \sigma ))</td>
<td>0.053</td>
</tr>
<tr>
<td></td>
<td>0.020_{-0.012}^{+0.015}</td>
<td>2.7 (1.6( \sigma ))</td>
<td>0.065</td>
</tr>
<tr>
<td>global with SBL</td>
<td>0.017_{-0.009}^{+0.007}</td>
<td>4.9 (2.2( \sigma ))</td>
<td>0.040</td>
</tr>
<tr>
<td></td>
<td>0.020_{-0.009}^{+0.008}</td>
<td>5.4 (2.3( \sigma ))</td>
<td>0.044</td>
</tr>
<tr>
<td>global with SBL (free norm)</td>
<td>0.010_{-0.006}^{+0.009}</td>
<td>3.1 (1.8( \sigma ))</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>0.013_{-0.007}^{+0.010}</td>
<td>3.3 (1.8( \sigma ))</td>
<td>0.041</td>
</tr>
<tr>
<td>global w/o SBL</td>
<td>0.023_{-0.008}^{+0.010}</td>
<td>9.0 (3.0( \sigma ))</td>
<td>0.052</td>
</tr>
<tr>
<td></td>
<td>0.030 ± 0.010</td>
<td>10.3 (3.2( \sigma ))</td>
<td>0.058</td>
</tr>
<tr>
<td>global w/o SBL (old fluxes)</td>
<td>0.012_{-0.007}^{+0.010}</td>
<td>2.9 (1.7( \sigma ))</td>
<td>0.042</td>
</tr>
<tr>
<td></td>
<td>0.017 ± 0.010</td>
<td>3.2 (1.8( \sigma ))</td>
<td>0.048</td>
</tr>
</tbody>
</table>
Outline

The reactor anomaly

$\theta_{13}$

Sterile neutrinos

Summary and outlook
oscillations with $\Delta m^2 \sim 1 \text{eV}^2$ may account for disappearance at baselines $L \lesssim 100$ m
3+1 and 3+2 best fit to SBL reactor data

fitting reactor data by adding one or two sterile neutrinos

\[ \chi^2_{\text{no osc}} = 59.6/59 \]
\[ \chi^2_{3+1} = 50.4/57 \]
\[ \chi^2_{3+2} = 44.5/55 \]

<table>
<thead>
<tr>
<th>( \Delta m^2 ) [eV^2]</th>
<th>( U_{e4} )</th>
<th>( \Delta m^2 ) [eV^2]</th>
<th>( U_{e5} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>((3+1))</td>
<td>0.45</td>
<td>0.117</td>
<td></td>
</tr>
<tr>
<td>((3+2))</td>
<td>0.46</td>
<td>0.115</td>
<td>0.93</td>
</tr>
</tbody>
</table>
3+1 and 3+2 fit to SBL reactor data

- Preference for sterile neutrino oscillations
- $\Delta \chi^2(3 + 1/\text{no-osc}) = 9.3 \rightarrow 99\% \text{ CL (2 dof)}$
- $\Delta \chi^2(3 + 2/\text{no-osc}) = 15.4 \rightarrow 99.6\% \text{ CL (4 dof)}$
- Old flux: $\Delta \chi^2 = 3.3(5.4)$ for 3+1 (3+2)
\[ \nu_\mu \rightarrow \nu_e \text{ data at the } E/L \sim 1 \text{ eV}^2 \text{ scale} \]

- **LSND** \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \), \( 87.9 \pm 22.4 \pm 6.0 \) excess events
  \[ P = (0.264 \pm 0.067 \pm 0.045)\% \sim 3.8\sigma \text{ away from zero} \]

- **MiniBooNE** \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \), \( \sim 2\sigma \) excess
  consistent with LSND in 2\( \nu \) framework

- **MiniBooNE** \( \nu_\mu \rightarrow \nu_e \)
  \( E > 475 \): no excess, \( E < 475 \): \( \sim 3\sigma \) excess (talk by G. Mills)

- **KARMEN** \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \), tight constraint on LSND region
  (slightly smaller \( L/E \) than LSND)
3+1 oscillations

In 3+1 schemes the appearance probability at short-baselines is effectively 2-ν oscillations:

\[ P_{\mu e} = \sin^2 2\theta_{\text{SBL}} \sin^2 \frac{\Delta m^2_{41} L}{4E} \]

with

\[ \sin^2 2\theta_{\text{SBL}} = 4|U_{e4}|^2|U_{\mu 4}|^2 \]

- no CP violation
- constraints from $\nu_e$ ($\nu_\mu$) disappearance experiments on $U_{e4}$ ($U_{\mu 4}$)
3+1 global

despite relaxed constraints from reactors on $U_{e4}$
no improvement of global 3+1 fit
Sterile neutrinos

3+2 appearance probability

\[ P_{\nu_{\mu} \rightarrow \nu_e} = 4 |U_{e4}|^2 |U_{\mu4}|^2 \sin^2 \phi_{41} \]
\[ + 4 |U_{e5}|^2 |U_{\mu5}|^2 \sin^2 \phi_{51} \]
\[ + 8 |U_{e4} U_{\mu4} U_{e5} U_{\mu5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta) \]

with the definitions

\[ \phi_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}, \quad \delta \equiv \text{arg} \left( U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^* \right) \]

- 3+2 osc. include the possibility of CP violation \[ \text{Karagiorgi 07} \]
- remember: MiniBooNE: neutrinos, LSND: anti-neutrinos
- good fit to appearance exps (even MB low-E) \[ \text{Maltoni, TS 07} \]
3+2 global fit

| $\Delta m^2_{41}$ | $|U_{e4}|$ | $|U_{\mu4}|$ | $\Delta m^2_{51}$ | $|U_{e5}|$ | $|U_{\mu5}|$ | $\delta/\pi$ | $\chi^2$/dof |
|-------------------|----------|----------|-------------------|----------|----------|-------------|-------------|
| 0.47              | 0.131    | 0.170    | 0.93              | 0.135    | 0.142    | 1.62        | 105.9/130   |

- $\Delta \chi^2$ (old vs new fluxes) = 15.5
- $\Delta \chi^2$ (3+1 vs 3+2) = 14.1 (99.3% CL, 4 dof)
3+2 best fit point

\[ \Delta \chi^2 \text{ between global bfp and app/disapp separate bfp:} \]

<table>
<thead>
<tr>
<th></th>
<th>LSND</th>
<th>MB\bar{\nu}</th>
<th>MB\nu</th>
<th>KAR</th>
<th>React</th>
<th>CDHS</th>
<th>Atmos</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.2</td>
<td>2.9</td>
<td>2.5</td>
<td>1.5</td>
<td>0.9</td>
<td>2.4</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Kopp, Maltoni, TS, 1103.xxxx
Other signatures of sterile neutrinos

- checked solar/KamLAND fit: $U_{e4}, U_{e5}$ similar effect as $U_{e3}$
- MINOS NC 1001.0336 analysis may give additional constraints
- Deficit in radioactive source experiments at Gallium exps C. Giunti
- Cosmology:

![Graph showing $N_s$ vs. $m_s$ (eV)]

- BBN: $N_s < 1.2$ (95% CL) Mangano, Serpico, 1103.1261

CMB, SDSS, HST
Hamann et al., 1006.5276

Talk by A. Melchiorri
Outline

The reactor anomaly

$\theta_{13}$

Sterile neutrinos

Summary and outlook
Summary

- slightly ambiguous status of $\theta_{13}$ due to new reactor fluxes: $\sin^2 \theta_{13} = 0.1 - 0.3$ with hints for $\theta_{13} > 0$ at $1.8 - 3.2\sigma$

- intriguing accumulation of hints for eV-scale sterile neutrinos (LSND/MiniBooNE/reactor/Gallium)
  3+2 model with two eV-scale neutrinos gives good fit to global data
Outlook $\theta_{13}$

Huber, Lindner, TS, Winter, 09; Mezzetto, TS, 10

Discovery potential at 3 $\sigma$ for NH

![Graph showing discovery potential at 3 $\sigma$ for NH with markers for T2K, DoubleChooz, RENO, DayaBay, and NOvA.]

Discovery potential at 3$\sigma$ in 2018

![Graph showing discovery potential at 3$\sigma$ in 2018 with markers for T2K, NOvA, Daya Bay, Double Chooz, and RENO.]

width beams: dependence on CP phase, DayaBay: syst. uncert. 0.18% - 0.6%

- one order of magnitude improvement within $\sim$ 5 years talks in next session
- can disentangle $\theta_{13}$ from effects of sterile neutrinos by near-far comparison (reactors: cancel flux uncert. + sterile $\nu$, beams: predict background from ND to avoid effects of sterile $\nu$ - check L/E!)
Outlook sterile neutrinos

how can we clarify the issue of eV-scale neutrinos?

▶ radioactive source experiments
Garvin et al, 1006.2103; Vergados, Novikov, 1006.3862; Grieb, Link, Raghavan, hep-ph/0611178;

▶ new experiment at CERN  talk by C. Rubbia

▶ LSND-like experiment at stopped pion source (ESS)  talk by H. Wacklin

▶ look for $\nu_\mu$ disappearance at the eV$^2$ scale

▶ signatures in IceCube (Deep Core)?  S. Coubey, 0709.1937

▶ etc