I. Neutrino oscillation anomalies

II. Models with one sterile neutrino

III. Models with two sterile neutrinos
I. Neutrino oscillation anomalies

Neutrino oscillations: where we are

- **Global 6-parameter fit (including \( \delta_{\text{CP}} \))**: 
  - **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + Borexino;
  - **Atmospheric**: SK-1 + SK-2 + SK-3 + SK-4;
  - **Reactor**: KamLAND + Chooz + Palo-Verde + Double-Chooz + Daya-Bay + Reno;
  - **Accelerator**: Minos (DIS+APP) + T2K (DIS+APP);

- **best-fit point and 1\(\sigma\) (3\(\sigma\)) ranges:**
  \[
  \theta_{12} = 33.48^{+0.77}_{-0.74} \left( ^{+2.42}_{-2.18} \right), \quad \Delta m_{21}^2 = 7.50^{+0.19}_{-0.17} \left( ^{+0.59}_{-0.47} \right) \times 10^{-5} \text{ eV}^2, \\
  \theta_{23} = \begin{cases} 
  42.2^{+0.1}_{-0.1} \left( ^{+11.1}_{-3.8} \right), \\
  49.4^{+1.6}_{-2.0} \left( ^{+3.9}_{-11.0} \right), 
  \end{cases} \quad \Delta m_{31}^2 = \begin{cases} 
  +2.458^{+0.002}_{-0.002} \left( ^{+0.141}_{-0.133} \right) \times 10^{-3} \text{ eV}^2, \\
  -2.373^{+0.047}_{-0.047} \left( ^{+0.141}_{-0.142} \right) \times 10^{-3} \text{ eV}^2, 
  \end{cases} \\
  \theta_{13} = 8.52^{+0.20}_{-0.21} \left( ^{-0.59}_{-0.65} \right), \quad \delta_{\text{CP}} = 251^{+67}_{-59} (\text{any});
  
- **neutrino mixing matrix:**
  \[
  |U|_{3\sigma} = \begin{pmatrix}
  0.801 & \rightarrow & 0.845 \
  0.225 & \rightarrow & 0.517 \\
  0.246 & \rightarrow & 0.529
  \end{pmatrix}
  \begin{pmatrix}
  0.514 & \rightarrow & 0.580 \
  0.441 & \rightarrow & 0.699 \\
  0.464 & \rightarrow & 0.713
  \end{pmatrix}
  \begin{pmatrix}
  0.137 & \rightarrow & 0.158 \
  0.614 & \rightarrow & 0.793 \\
  0.590 & \rightarrow & 0.776
  \end{pmatrix}.
  

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The LSND experiment observed an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam ($E_\nu \sim 30$ MeV, $L \sim 35$ m) \cite{3};

the Karmen collaboration did not confirm the claim, but couldn’t fully exclude it either \cite{4};

the signal is compatible with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations provided that $\Delta m^2 \gtrsim 0.1$ eV$^2$;

on the other hand, global neutrino data give (at $3\sigma$):
\[
\Delta m^2_{\text{sol}} \approx 7.5 \pm 0.6 \times 10^{-5} \text{ eV}^2,
\]
\[
|\Delta m^2_{\text{atm}}| \approx 2.4 \pm 0.2 \times 10^{-3} \text{ eV}^2;
\]

hence, to explain LSND with mass-induced $\nu$ oscillations one needs at least one more neutrino mass eigenstate;

MiniBooNE: much larger $E_\nu$ and $L$ but similar $L/E_\nu$ . . .

\[3\] A. Aguilar-Arevalo et al. [LSND collab], Phys. Rev. D 64 (2001) 112007 [hep-ex/0104049].
I. Neutrino oscillation anomalies

$\nu_\mu \rightarrow \nu_e$ appearance: MiniBooNE neutrino data

- Statistics: $5.58 \times 10^{20}$ POT, then just improved analysis;
- is $\nu$ signal compatible with $2\nu$ oscillations? \( P_{\text{osc}} \approx 1\% \Rightarrow \text{no it isn't} \) [5]; \( P_{\text{osc}} \approx 6\% \Rightarrow \text{maybe it is} \) [6];
- do MB $\nu$ data rule out the LSND $\bar{\nu}$ signal? 2007: yes [5]; 2012: not really [6].


Talks: this afternoon
I. Neutrino oscillation anomalies

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance: MiniBooNE antineutrino data

- New data presented at Neutrino 2012, statistics doubled ($\rightarrow 11.27 \times 10^{20} \text{ POT}$) [6];
- compatibility with $\nu$ data: \[
\begin{align*}
&\text{low-energy excess increased} \Rightarrow \text{better agreement}; \\
&\text{mid-energy excess reduced} \Rightarrow \text{better agreement};
\end{align*}
\]
- is $\bar{\nu}$ signal compatible with $2\nu$ oscillations? $P_{\text{osc}} = 67.5\% \Rightarrow \text{definitely yes}$ [6, 7];
- is MB-$\bar{\nu}$ signal compatible with LSND? Yes, irrespective of the energy threshold.


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I. Neutrino oscillation anomalies

\[ \bar{\nu}_e \text{ disappearance: the reactor anomaly} \]

- In [8, 9] the reactor \( \bar{\nu} \) fluxes was reevaluated;
- the new calculations result in a small increase of the flux by about 3.5%;
- hence, all reactor short-baseline (RSBL) finding no evidence are actually observing a deficit;
- this deficit could be interpreted as being due to SBL neutrino oscillations;
- no visible dependence on \( L \Rightarrow \Delta m^2 \gtrsim 1 \text{ eV}^2 \);

\[ \Rightarrow \text{ new "hint" in favor of SBL oscillations, independent of LSND & MiniBooNE.} \]


\[ \Rightarrow \text{Talk: Huber} \]

\[ \Rightarrow \text{Talk: Lasserre} \]
I. Neutrino oscillation anomalies

\( \bar{\nu}_e \) recent data: Daya-Bay

- Daya-Bay **confirms** the deficit in reactor’s flux;
- again, no visible dependence on \( L \Rightarrow \) excluded region from absence of spectral distorsion.

⇒ Talk: Peng


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I. Neutrino oscillation anomalies

$\bar{\nu}_e$ recent data: 5 MeV excess

- Neutrino 2014: RENO [16] reported an excess of events around 5 MeV;
- excess independent of baseline $L \Rightarrow$ not related to neutrino oscillations;
- confirmed by Daya-Bay [17], Double-Chooz [15] and also Chooz [14];
- more info: ⇒ Talks: Huber, Lasserre

⇒ Talk: Kim

⇒ Talk: Crespo-Anadón

⇒ Talk: Peng

[15] H. de Kerret [Double-Chooz collab], talk at Neutrino 2014, Boston, USA.

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**Neutrino oscillation anomalies**

**ν_e disappearance: the gallium anomaly**

- The $^{71}\text{Ga} \rightarrow ^{71}\text{Ge}$ neutrino capture cross-section, relevant for the GALLEX and SAGE solar neutrino experiments, was calibrated with intense $^{51}\text{Cr}$ and $^{37}\text{Ar}$ neutrino sources;
- these measurements show a significant deficit with respect to the predicted values:

\[
\begin{align*}
R_1(\text{Cr}) &= 0.94 \pm 0.11 \quad [18] \\
R_2(\text{Cr}) &= 0.80 \pm 0.10 \quad [18] \\
R_3(\text{Cr}) &= 0.93 \pm 0.12 \quad [19] \\
R_4(\text{Ar}) &= 0.77 \pm 0.08 \quad [20]
\end{align*}
\]

\[\Rightarrow 0.84 \pm 0.05\]

- such 3σ deficit can be interpreted in terms of ν oscillations;
- once again, data suggests $\Delta m^2 \gtrsim 1 \text{ eV}^2$.

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I. Neutrino oscillation anomalies

\( \nu_e \) disappearance: T2K near-detector data

- Recent measurement of the sub-leading \( \nu_e \) component at the ND280 near detector of the T2K beam;
- outcome: small deficit with respect to expected neutrino flux;
- interpretation: oscillations with \( \Delta m^2 \gtrsim 0.1 \text{ eV}^2 \); however no-oscillations still allowed at 94% CL.

\[ \Rightarrow \text{Talk: Giganti} \]


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II. Models with one sterile neutrino

\[ \nu_e \text{ disappearance} \]

- Relevant experiments:
  - T2K-ND \((\nu)\)
  - SBL reactors \((\bar{\nu})\)
  - LBL reactors \((\bar{\nu})\)
  - KamLAND \((\bar{\nu})\)
  - Galilium \((\nu)\)
  - Solar \((\nu)\)
  - \(^{12}\)C \((\nu)\)

\(\nu_e \rightarrow \nu_e\) appearance

- Relevant experiments:
  - MiniBooNE \((\nu, \bar{\nu})\)
  - E776 \((\nu, \bar{\nu})\)
  - KARMEN \((\bar{\nu})\)
  - NOMAD \((\nu)\)
  - ICARUS \((\nu)\)
  - OPERA \((\nu)\)

Note: \(\bar{\nu}_e \rightarrow \bar{\nu}_e\) and \(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\) probe the same \(\Delta m^2\) but a different mixing angle \(\Rightarrow\) mutual comparison requires embedding them into a general oscillation model.


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II. Models with one sterile neutrino

Four neutrino mass models

- Approximation: $\Delta m^2_{\text{SOL}} \ll \Delta m^2_{\text{ATM}} \ll \Delta m^2_{\text{SBL}} \Rightarrow 6$ different mass schemes:

- Total: $3 \Delta m^2$, $6$ angles, $3$ phases. Different set of experimental data partially decouple:

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(2+2): ruled out by solar and atmospheric data

- in (2+2) models, fractions of $\nu_s$ in solar ($\eta_s$) and atmos ($1 - d_s$) add to one $\Rightarrow \eta_s = d_s$;
- $3\sigma$ allowed regions $\eta_s \leq 0.31$ (solar) and $d_s \geq 0.63$ (atmos) do not overlap; superposition occurs only above $4.5\sigma$ ($\chi^2_{PC} = 19.9$);
- the $\chi^2$ increase from the combination of solar and atmos data is $\chi^2_{PG} = 28.6$ (1 dof), corresponding to a PG $= 9 \times 10^{-8}$ [23].


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II. Models with one sterile neutrino

(3+1): appearance versus disappearance

• (3+1): $P_{\nu_\mu \rightarrow \nu_e} \propto |U_{e4} U_{\mu 4}|^2$ with
  \[
  \frac{|U_{e4}|^2}{|U_{\mu 4}|^2} \propto P_{\nu_e \rightarrow \nu_e},
  \frac{|U_{\mu 4}|^2}{|U_{e4}|^2} \propto P_{\nu_\mu \rightarrow \nu_\mu};
  \]

• hence, $P_{\nu_\mu \rightarrow \nu_e} > 0$ requires
  \[
  \begin{cases}
  P_{\nu_e \rightarrow \nu_e} > 0, \\
  P_{\nu_\mu \rightarrow \nu_\mu} > 0;
  \end{cases}
  \]

¿? are $\nu_\mu \rightarrow \nu_\mu$ searches compatible with this?

$\nu_\mu$ disappearance: present status

• Many experiments have been performed:
  - CDHS (\(\nu\))
  - MINOS CC (\(\nu\))
  - MiniBooNE (\(\nu, \bar{\nu}\))
  - MINOS NC (\(\nu\))
  - SciBooNE (\(\nu, \bar{\nu}\))
  - SK atmos (\(\nu, \bar{\nu}\))

  • no hint of $\nu_\mu$ disappearance has been observed;

  • bound on $|U_{\mu 4}|^2$ may be in tension with other data . . .


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\( \nu_\mu \) disappearance: recent atmospheric and SBL data

- New Super-K atmospheric analysis \([24, 25]\) probes \( \nu_\mu \) mixing with heavy sterile state;
- combined analysis of MiniBooNE & SciBooNE, both for \( \nu \) \([26]\) and \( \bar{\nu} \) \([27]\);
- new MINOS analysis \([28]\) further improve bound on \( \nu_\mu \) disapp. \( \Rightarrow \) Talk: Patterson

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### References


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II. Models with one sterile neutrino

(3+1): tension among data samples

- Limits on $\nu_e \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ disappearance imply a bound on the $\nu_\mu \rightarrow \nu_e$ appearance probability;
- such bound is stronger than what is required to explain the LSND and MiniBooNe excesses [A];
- hence, severe tension arises between APP and DIS data: $\chi^2_{PG}/\text{dof} = 18.0/2 \Rightarrow PG = 0.012\%$ [22];
- a similar result is obtained when comparing “positive” and “null” evidence for sterile $\nu$’s [B];
- in summary, (3+1) models fail because:
  - the low-energy MiniBooNE excess is poorly fitted;
  - MiniBooNE ($\nu$) and LSND ($\bar{\nu}$) do not really agree;
  - there is tension between APP And DIS data.

II. Models with one sterile neutrino

(3+1): comparison with other analyses

- A few independent analyses of APP versus DIS compatibility have been presented;
- results of [29] very similar to ours. (3+1) ruled out: $\chi^2_{PG}/\text{dof} = 17.8/2 \Rightarrow PG = 0.013\%$;
- results of [30] differ! \[ \begin{align*} 
\text{(3+1) poor: } & \chi^2_{PG}/\text{dof} = 12.7/2 \Rightarrow PG = 0.2\% \ (\text{MB } E_\nu > 200 \text{ MeV}), \\
\text{(3+1) good: } & \chi^2_{PG}/\text{dof} = 4.8/2 \Rightarrow PG = 9\% \ (\text{MB } E_\nu > 475 \text{ MeV}).
\end{align*} \]

The MiniBooNE excess

- MiniBooNE observed an overall $3.8\sigma$ excess, mostly at low energy [31];
- although no longer “in open disagreement”, $\nu$ and $\bar{\nu}$ signals are not really equivalent either. For example:
  \[
P_{2\nu} = \begin{cases} 
    6.1\% & \text{for } \nu; \\
    67.5\% & \text{for } \bar{\nu}; 
  \end{cases}
\]
- former omission of low-energy $\nu$ bins ($E_{\nu}^{QE} < 475$ MeV) based on the hypothesis of two-flavor oscillations;
- is it possible to do something better about low-energy data in more sophisticated models?

II. Models with two sterile neutrinos

Explaining the MiniBooNE excess with two sterile neutrinos

- With **one** extra sterile neutrino, \( m_4 \):

  \[
P_{\mu e}^{4\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 \phi_{41} \quad \text{with} \quad \phi_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E};
\]

- for large energy \( P_{\mu e}^{4\nu} \) drops as \( 1/E^2 \);

- however, the low-energy MB excess is much sharper (\( \sim 1/E^3 \));

\( \Rightarrow \) it is very hard to account for the MB excess with only one extra sterile neutrino.

- On the other hand, with **two** extra neutrinos, \( m_4 \) and \( m_5 \):

  \[
P_{\mu e}^{5\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2 \phi_{51} + 8|U_{e4} U_{e5} U_{\mu 4} U_{\mu 5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta);
\]

- terms of order \( 1/E^2 \) cancel if \( \delta = \pi \) and \( |U_{e4} U_{\mu 4}|\Delta m_{41}^2 = |U_{e5} U_{\mu 5}|\Delta m_{51}^2 \);

\( \Rightarrow \) with two extra sterile states it is possible to fit the MB low-energy excess \([32]\).


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III. Models with two sterile neutrinos

Reconciling MiniBooNE and LSND in (3+2) models

- **Trick:** use the CP phase $\delta = \arg(U_e^* U_\mu U_\mu^* U_\nu)$ to differentiate $\nu$ (MB) from $\bar{\nu}$ (LSND):

$$P_{\mu\nu}^5 = 4|U_{e4}|^2|U_{4\mu}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2|U_{5\mu}|^2 \sin^2 \phi_{51} + 8|U_{e4} U_{e5} U_{\mu4} U_{\mu5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta);$$

- note that $\delta = \pi + \epsilon$ and $|U_{e4} U_{\mu4}| \Delta m_{41}^2 \approx |U_{e5} U_{\mu5}| \Delta m_{51}^2$ to suppress MB probability [32].

III. Models with two sterile neutrinos

Fitting all $\nu_\mu \rightarrow \nu_e$ appearance data with two sterile $\nu$’s

<table>
<thead>
<tr>
<th>Model</th>
<th>dof</th>
<th>$\chi^2_{\text{min}}$</th>
<th>GOF</th>
<th>$\chi^2_{(3+1)} - \chi^2_{\text{min}}$</th>
<th>CL</th>
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<td>(3+1)</td>
<td>68-2</td>
<td>87.9</td>
<td>3.7%</td>
<td>—</td>
<td>—</td>
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<tr>
<td>(3+2)</td>
<td>68-5</td>
<td>72.7</td>
<td>19%</td>
<td>15.2</td>
<td>99.8%</td>
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<tr>
<td>(1+3+1)</td>
<td>68-5</td>
<td>74.6</td>
<td>15%</td>
<td>13.3</td>
<td>99.6%</td>
</tr>
</tbody>
</table>


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III. Models with two sterile neutrinos

**Status of (3+2) models from global data**

- (3+2) models suffer from severe tension between **APP** and **DIS** data: $\text{PG}=0.53\%$ [34];
- the situation worsen when **MiniBooNE** low-E data are included: $\text{PG}=0.0034\%$ [22];
- (1+3+1) works somewhat better ($\text{PG}=0.21\%$ [22]), but has stronger problems with **cosmology** since the sum of neutrino masses ($\sum m_\nu$) is larger.

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Most of the present data from solar, atmospheric, reactor and accelerator experiments are well explained by the $3\nu$ oscillation hypothesis;

however, a few experiments exhibit deviations from the “standard” $3\nu$ scenario:

- LSND & MiniBooNE observe excesses of $\bar{\nu}_e$ events in $\bar{\nu}_\mu$ beams;
- SBL reactors observe a deficit with respect to the expected $\bar{\nu}$ fission flux;
- gallium experiments exposed to radioactive sources also find a deficit;

sterile neutrino models fail to explain satisfactorily all the experimental data:

<table>
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<th>Requirement</th>
<th>$(3+0)$</th>
<th>$(2+2)$</th>
<th>$(3+1)$</th>
<th>$(3+2)$</th>
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<tr>
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<tr>
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<tr>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$: MB low-energy excess</td>
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<tr>
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</table>

⇒ we are still far from the solution of the LSND puzzle. Need more data!  ⇒ see next talk