New anomalies in the solar sector?

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Excellence Cluster ‘Universe’
Two weak anomalies in the solar sector:
  I - The solar/KamLAND $\theta_{12}$ mismatch;
  II - The anomalous solar spectrum behavior.

Two possible (classes of) explanations:
A - Standard/non-standard kinematics ($\theta_{13}/\theta_{14}$);
B - New dynamics (NSI).

Conclusions
Introduction
2011 status of the standard 3ν mass-mixing parameters
[update of Fogli et al., arXiv:0805:2517 (in preparation)]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\delta m^2/10^{-5} \text{ eV}^2$</th>
<th>$\sin^2 \theta_{12}$</th>
<th>$\sin^2 \theta_{13}$</th>
<th>$\sin^2 \theta_{23}$</th>
<th>$\Delta m^2/10^{-3} \text{ eV}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best fit</td>
<td>7.54</td>
<td>0.307</td>
<td>0.014</td>
<td>0.42</td>
<td>2.36</td>
</tr>
<tr>
<td>1σ range</td>
<td>7.32–7.79</td>
<td>0.291–0.325</td>
<td><strong>0.006–0.023</strong></td>
<td>0.38–0.51</td>
<td>2.26–2.48</td>
</tr>
<tr>
<td>2σ range</td>
<td>7.14–7.99</td>
<td>0.275–0.342</td>
<td>&lt;0.033</td>
<td>0.36–0.59</td>
<td>2.17–2.57</td>
</tr>
<tr>
<td>3σ range</td>
<td>6.98–8.17</td>
<td>0.259–0.360</td>
<td>&lt;0.042</td>
<td>0.33–0.64</td>
<td>2.07–2.67</td>
</tr>
</tbody>
</table>
Two anomalies in the solar sector
I - Solar & KamLAND prefer different $\theta_{12}$ values
II - No MSW upturn in the $^8\text{B} \nu$ spectrum

BOREXINO

SNO LETA

SK-III
Standard and non-standard kinematical effects

$\theta_{13} \text{ vs } \theta_{14}$
Tension can be alleviated by non-zero $\theta_{13}$

For $\theta_{13} = 0$
Solar and KamLAND prefer different values of $\theta_{12}$

For $\theta_{13} > 0$
Solar data prefer higher $\theta_{12}$
KamLAND prefers lower $\theta_{12}$

But the same task can be accomplished by $\theta_{14}$

\[
\begin{aligned}
CC & \sim \Phi_B P_{ee} \\
NC & \sim \Phi_B (1-P_{es}) \\
ES & \sim \Phi_B (P_{ee} + 0.15 P_{ea})
\end{aligned}
\]

Solar $\nu$ sensitive to $P_{es}$

CC/NC (SNO) & ES (SK)

Different correlations

Similar indication at $1.8\sigma$

We expect a degeneracy among $\theta_{13}$ and $\theta_{14}$


(PRD accepted)
Indistinguishability of $\theta_{13}$ from $\theta_{14}$

Complete degeneracy

Solar sector essentially sensitive to $\sim U_{e3}^2 + U_{e4}^2$

Hint of $\nu_e$ mixing with states others than $(\nu_1, \nu_2)$

Different probes are necessary to determine if $\nu_e$ mixes with $\nu_3$ or $\nu_4$

(PrD accepted)
But kinematics cannot explain the second anomaly

Spectrum unaffected in both cases

\[ \theta_{13} \neq 0 \quad \theta_{14} = 0 \quad (3\nu) \]

\[ P_{ee} = c_{13}^4 P_{ee}^{2\nu} \begin{vmatrix} \rightarrow Vc_{13}^2 \\ V \end{vmatrix} + s_{13}^4 \]

\[ P_{es} = 0 \]

\[ \theta_{13} = 0 \quad \theta_{14} \neq 0 \quad (4\nu) \]

\[ P_{ee} = c_{14}^4 P_{ee}^{2\nu} \begin{vmatrix} \rightarrow Vc_{14}^2 \\ V \end{vmatrix} + s_{14}^4 \]

\[ P_{es} \approx s_{14}^2 P_{ee}^{2\nu} \begin{vmatrix} \rightarrow Vc_{14}^2 \\ V \end{vmatrix} + s_{14}^2 \]

Rescaling of \( V \) induces minor dynamical effects
Non-standard dynamics:

New flavor-changing interactions
The S-K tension from a different perspective

From this perspective, it is meaningful to hypothesize that the disagreement may result from some unaccounted effect intervening in the dynamics of solar $\nu$ transitions.

Non-standard interactions (NSI) offer one such possibility, as they can alter the coherent forward scattering of solar $\nu$'s on the constituents of the ordinary matter (Wolfestein 1978).
Coherent forward scattering with NSI

\[ \nu_\alpha \rightarrow \nu_\alpha \quad \text{Z} \quad f \rightarrow f \]

\[ \nu_e \rightarrow \nu_e \quad \text{W} \quad e^- \rightarrow e^- \]

\[ \nu_\alpha \rightarrow \nu_\beta \quad ? \quad f \rightarrow f \]

Standard interaction terms

NSI term(s)

NSI described by an effective four-fermion operator

\[ O^{\text{NSI}}_{\alpha\beta} \sim \bar{\nu}_\alpha \nu_\beta \bar{f} f \]

Subweak strength \( \mathcal{E} G_F \)

\[ (\alpha, \beta) = e, \mu, \tau \]

\[ f \equiv (e, u, d) \]
Explaining the first anomaly

How $\varepsilon$ counterbalances $\theta_{12}$

At high energies, effect of $\theta_{12}$ is balanced by NSI, ... with an interesting “side effect”: spectrum is flatter ...

* $\varepsilon = \varepsilon_{e\mu} c_{23} - \varepsilon_{e\tau} s_{23}$
How to quantify such spectral distortions

The response functions of SK, SNO, Borexino are centered around $E_0 = 10$ MeV, where they have maximal sensitivity.

Assuming a regular behavior for the survival probability we can parameterize its high energy behavior as a second order polynomial:

$$P_{ee} = c_0 + c_1 (E-E_0) + c_2 (E-E_0)^2$$

It is then possible to:

1) Extract the coefficients from the combination of all the experiments sensitive to the high-energy neutrinos.

2) Check where a given theor. model (standard MSW, +NSI, etc.) “lives” in the space of the coefficients $c_i$’s.
High-E polynomial expansion is accurate

\[ \Delta m^2 = 7.67 \times 10^{-5} \text{ eV}^2 \]

\[
\begin{array}{ccc}
S_{12}^2 & \varepsilon & 2\nu \\
0.312 & 0 & 2\nu \\
0.327 & -0.16 & 2\nu + \text{NSI}
\end{array}
\]

\[ P_{ee} \]

\[ E \ (\text{MeV}) \]
NSI can explain also the second anomaly


NSI gains a $\Delta \chi^2 \sim -2.0$ from better description of the spectrum
NSI are favored at the $\sim 2\sigma$ level

New kinematics or new dynamics?

Spectral info tends to favor NSI over $\theta_{13}$ (or $\theta_{14}$)

Conclusions

- The solar sector presents two weak anomalies;

- Kinematical effects induced by $\theta_{13}$ (standard) or $\theta_{14}$ (non-standard) can alleviate (only) one of them;

- New dynamical effects (NSI) can explain both;

- New solar low-energy data and corroboration by the rest of $\nu$ phenomenology indispensable.
Back up
Solar hint of $\theta_{13} > 0$ depends on the reactor fluxes

KamLAND prefers larger values of $\theta_{13}$ with the new (higher) $\nu$ fluxes as a bigger rate suppression is needed in this case
The 3+1 Scheme

The 4th \( \nu \) state induces a small perturbation of the 3-flavor framework.

\[ |U_{s4}| \sim 1 \]

\[ \Delta m_{\text{sol}}^2 \]

\[ \Delta m_{\text{atm}}^2 \]

\[ \Delta m_{\text{new}}^2 > 1eV^2 \]

* Solar sector alone cannot distinguish the 3+1 scheme from a scheme where also \( U_{s3} \) is big (but this disfavored by the atmospheric sector).

* Hierarchy: reciprocal ordering of \( (\nu_3, \nu_4) \) & respect to \( (\nu_1, \nu_2) \) unknown.
The reactor anomaly and the Gallium calibration problem

In a $2\nu$ framework:

\[ P_{ee} \approx 1 - \sin^2 2\theta_{new} \sin^2 \frac{\Delta m_{new}^2 L}{4E} \]
\[ \sin^2 2\theta_{new} \approx 0.17 \pm 0.1 \text{ (95\%)} \]

In a $3+1$ scheme:

\[ P_{ee} = 1 - 4 \sum_{j>k} U_{ej}^2 U_{ek}^2 \sin^2 \frac{\Delta m_{jk}^2 L}{4E} \]
\[ \Delta m_{sol}^2 \ll \Delta m_{atm}^2 \ll \Delta m_{new}^2 \]
\[ \sin^2 \theta_{new} \approx U_{e4}^2 = \sin^2 \theta_{14} \]
KamLAND in a 3+1 scheme

\[ P_{ee} = 1 - 4 \sum_{j>k} U_{ej}^2 U_{ek}^2 \sin^2 \frac{\Delta m_{jk}^2 L}{4E} \]

\[ \Delta m_{sol}^2 \ll \Delta m_{atm}^2 \ll \Delta m_{new}^2 \]

\[ \Delta m_{atm}^2 \text{-driven osc. averaged} \]

\[ \Delta m_{new}^2 \]

\[ P_{ee} = (1 - U_{e3}^2 - U_{e4}^2)^2 P_{ee}^{2\nu} + U_{e3}^4 + U_{e4}^4 \]

\[ U_{e3}^2 = c_{14}s_{13}^2 \quad U_{e4}^2 = s_{14}^2 \]

Exact degeneracy between \( U_{e3} \) and \( U_{e4} \)
Solar $\nu$ conversion in a 3+1 scheme

\[ i \frac{d}{dx} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = H \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} \]

\[ H = U K U^T + V(x) \]

\[ K = \frac{1}{2E} \text{diag}(k_1, k_2, k_3, k_4) \quad k_i = \frac{m_i^2}{2E} \]

Useful to write the mixing matrix as*:

\[ U = R_{23} R_{24} R_{34} R_{14} R_{13} R_{12} \]

$\theta_{14}=\theta_{24}=\theta_{34}=0 \quad \rightarrow \quad 3$-flavor case

\[ V = \text{diag}(V_{CC}, 0, 0, -V_{NC}) \]

\[ V_{CC} = \sqrt{2} G_F N_e \quad V_{NC} = \frac{1}{2} \sqrt{2} G_F N_n \]

* We assume $U$ real but in general it can be complex due to CP-odd phases
**Change of basis:**

\[ \nu' = (R_{23} S R_{13})^T \nu = A^T \nu = R_{12} U^T \]

**In the new basis:**

\[ H' = A^T H A = R_{12} K R_{12}^T + R_{13}^T S^T V S R_{13} \]

**At zero\(^{th}\) order in:**

\[ \frac{V}{k_{atm}} \text{ and } \frac{V}{k_{new}} \]

\[ H' \sim \begin{pmatrix} H_{2\nu}' & \vdots \\ \vdots & \ddots \end{pmatrix} \]

The 3\(^{rd}\) and 4\(^{th}\) state evolve independently from the 1\(^{st}\) and 2\(^{nd}\)

The dynamics reduces to that of a two neutrino system
Diagonalization of the Hamiltonian

The 2x2 Hamiltonian is diagonalized by a 1-2 rotation

\[ \tilde{R}_{12}^T H'_{2
u} \tilde{R}_{12} = diag(\tilde{k}_1, \tilde{k}_2) \]

which defines the solar mixing angle in matter

\[ \tilde{\theta}_{12}(x) \]

wavenumbers in matter

\[ \tilde{k}_i \]

The starting Hamiltonian is then diagonalized by

\[ \tilde{U} = A \tilde{R}_{12} \]

\[ \tilde{U}^T H \tilde{U} = diag(\tilde{k}_1, \tilde{k}_2, k_3, k_4) \]

For \( \nu_3 \) and \( \nu_4 \) (averaged) vacuum-like propagation
The 2x2 Hamiltonian: \[ H_{2\nu}^\prime = H_{2\nu}^{\prime \text{kin}} + H_{2\nu}^{\prime \text{dyn}} \]

\[
H_{2\nu}^{\prime \text{kin}} = \begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \end{pmatrix} \begin{pmatrix} -k_{s\omega}/2 & 0 \\ 0 & k_{s\omega}/2 \end{pmatrix} \begin{pmatrix} c_{12} & -s_{12} \\ s_{12} & c_{12} \end{pmatrix}
\]

\[ k_{s\omega} = \frac{m_2^2 - m_1^2}{2E} \]

\[
H_{2\nu}^{\prime \text{dyn}} = V_{CC}(x) \begin{pmatrix} \gamma^2 + r(x)\alpha^2 & r(x)\alpha\beta \\ r(x)\alpha\beta & r(x)\beta^2 \end{pmatrix}^* \]

\[ r(x) = -\frac{V_{NC}}{V_{CC}} = \frac{1}{2} \frac{N_n(x)}{N_e(x)} > 0 \]

\[ \begin{align*}
\alpha^2 + \beta^2 &= U_{s1}^2 + U_{s2}^2 \\
\gamma^2 &= 1 - (U_{e3}^2 + U_{e4}^2)
\end{align*} \]

\[ \begin{align*}
\alpha &= c_{24}(s_{34}s_{13} - c_{34}s_{14}c_{13}) \\
\beta &= -s_{24} \\
\gamma &= c_{14}c_{13}
\end{align*} \]

All the dynamical effects induced by the 4th (and 3rd) state are 2nd order in the \( s_{ij} \): small deviations from the standard MSW.

But important new kinematical effects are present ...

For adiabatic propagation (valid for small deviations around the LMA)

\[
P_{ee} = \sum_{i=1}^{4} U_{ei}^2 \tilde{U}_{ei}^2 = U_{e1}^2 \tilde{U}_{e1}^2 + U_{e2}^2 \tilde{U}_{e2}^2 + U_{e3}^2 + U_{e4}^2
\]

\[
P_{es} = \sum_{i=1}^{4} U_{si}^2 \tilde{U}_{ei}^2 = U_{s1}^2 \tilde{U}_{e1}^2 + U_{s2}^2 \tilde{U}_{e2}^2 + U_{s3}^2 \tilde{U}_{e3}^2 + U_{s4}^2 \tilde{U}_{e4}^2
\]

Expressions for \(U_{ei}'s\)
(always valid)

\[
\begin{align*}
U_{e1}^2 &= c_{14}^2 c_{13}^2 c_{12}^2 \\
U_{e2}^2 &= c_{14}^2 c_{13}^2 s_{12}^2 \\
U_{e3}^2 &= c_{14}^2 s_{13}^2 \\
U_{e4}^2 &= s_{14}^2
\end{align*}
\]

\[
\begin{align*}
\sim 1 - s_{14}^2 - s_{13}^2
\end{align*}
\]

Expressions for \(U_{si}'s\)
(valid for \(\theta_{24} = \theta_{34} = 0\))

\[
\begin{align*}
U_{s1}^2 &= s_{14}^2 c_{13}^2 c_{12}^2 \\
U_{s2}^2 &= s_{14}^2 c_{13}^2 s_{12}^2 \\
U_{s3}^2 &= s_{14}^2 s_{13}^2 \\
U_{s4}^2 &= c_{14}^2 c_{13}^2 \\
\sim s_{14}^2 \\
\sim 0 \\
\sim 1 - s_{14}^2
\end{align*}
\]

The elements of \(\tilde{U}\) are obtained replacing \(\theta_{12}\) with \(\tilde{\theta}_{12}\)
calculated in the production point (near the sun center)
The SBL+Ga anomaly lifts the degeneracy in favor of $\theta_{14}$ at the "expense" of $\theta_{13}$.

Global indication for $\theta_{14}>0$ at $\sim 3.4\sigma$
Assuming $\theta_{13}=0$
$\theta_{14}>0$ at almost $4\sigma$
3-flavor evolution in the presence of NSI

Evolution in the flavor basis:
\[ i \frac{d}{dx} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = H \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \]

H contains three terms:
\[ H = H_{\text{kin}} + H_{\text{std}} + H_{\text{NSI}} \]

Kinematics
\[ H_{\text{kin}} = U \begin{pmatrix} -\delta k/2 & 0 & 0 \\ 0 & +\delta k/2 & 0 \\ 0 & 0 & k/2 \end{pmatrix} U^\dagger \]
\[ \delta k = \delta m^2/2E \]
\[ k = m^2/2E \]

Standard MSW dynamics
\[ H_{\text{std}}^{\text{dyn}} = \text{diag}(V, 0, 0) \]
\[ V(x) = \sqrt{2} G_F N_e(x) \]

Non-standard dynamics
\[ (H_{\text{dyn}}^{\text{NSI}})_{\alpha\beta} = \sqrt{2} G_F N_f(x) \epsilon_{\alpha\beta} \]
Reduction to an effective two flavor dynamics

One mass scale approximation:

\[ P_{ee} = c_{13}^4 P_{ee}^{\text{eff}} + s_{13}^4 \]

\[ i \frac{d}{dx} \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix} = H^{\text{eff}} \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix} \]

\[ H^{\text{eff}} = V(x) \begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} + \sqrt{2} G_f N_d(x) \begin{pmatrix} 0 & \varepsilon \\ \varepsilon' \end{pmatrix} \]

For \( \theta_{13} = 0 \):

\[ \varepsilon = -\varepsilon_{e\mu} c_{23} - \varepsilon_{e\tau} s_{23} \]

\[ \varepsilon' = -2\varepsilon_{\mu\tau} s_{23} c_{23} \]

Parameter space:

\[ [\delta m^2, \theta_{12}, \varepsilon] \]
Before the new spectral info $\theta_{13}$ and NSI were degenerate