Illuminating LMA-Dark solution and superlight sterile neutrinos by intermediate baseline reactor neutrino experiments

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IPM
Outline of my talk

• Review: Solar Neutrino anomaly and MSW effect
• Some tension: suppression of low energy upturn
• Superlight Sterile Neutrino Scenario (SSNS)
• Testing SSNS via intermediate baseline reactor experiments: JUNO and RENO-50
• Summary
• Non-Standard Neutrino Interactions (NSI)
• LMA-Dark solution
• Testing LMA-Dark solution via intermediate baseline reactor experiments: JUNO and RENO-50
• Summary
Solar neutrinos

- Proton fusion: 
  \[ 4p \rightarrow He + 2e^+ + 2\nu_e \]
Solar Neutrino spectrum

[Graph showing the Solar Neutrino spectrum with various reactions and their corresponding neutrino fluxes.]
Detection thresholds

Borexino threshold=0.25 MeV

Started data taking in 2007

Liquid scintillator
Homestake

- Gold mine in South Dakota-1960s-1994
- Raymond Davis and John Bahcall

\[ \nu_e + \text{Cl} \rightarrow e + \text{Ar} \]

- Observed/predicted=1/3

Davis, Harmer and Hoffman, PRL (1968)

- Confirmed by Kamiokande, SAGE, GALLEX, Super-kamiokande and SNO
Solar Neutrino Anomaly

- SM: Lepton flavor conservation

Solution: Lepton flavor violation
PMNS mixing matrix

\[ \nu_\alpha = \sum_i U_{\alpha i} \nu_i \]

\( U_{\alpha i} \) is a unitary matrix.

\[ \sum_i U_{\alpha i} U_{\beta i}^* = \delta_{\alpha \beta} \quad \sum_{\alpha} U_{\alpha i} U_{\alpha j}^* = \delta_{ij} \]
Propagation in matter

\[ i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix} = \mathcal{H} \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix} \]

\[ \mathcal{H} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \cdot \begin{pmatrix} 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} \end{pmatrix} \cdot \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} + \begin{pmatrix} V_e & 0 \\ 0 & V_a \end{pmatrix} \]

\[ V_e = \sqrt{2} G_F (n_e - n_n/2) \quad V_a = -G_F n_n / \sqrt{2} \]
KamLAND massacre!

Magnetic transition moment solution
LMA-solution

\[ \theta_{12} = (33.48^{+0.78}_{-0.75})^\circ \quad \Delta m^2_{21} = 7.50^{+0.19}_{-0.17} \times 10^{-5} \text{ eV}^2 \]

- M.C. Gonzalez-Garcia, Michele Maltoni, Thomas Schwetz, arXiv:1409.5439
<table>
<thead>
<tr>
<th></th>
<th>Normal Ordering ($\Delta\chi^2 = 0.97$)</th>
<th></th>
<th>Inverted Ordering (best fit)</th>
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<th>Any Ordering</th>
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<tr>
<td></td>
<td>bfp $\pm 1\sigma$</td>
<td>3$\sigma$ range</td>
<td>bfp $\pm 1\sigma$</td>
<td>3$\sigma$ range</td>
<td>3$\sigma$ range</td>
<td></td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$0.304^{+0.013}_{-0.012}$</td>
<td>$0.270 \rightarrow 0.344$</td>
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<td>$0.270 \rightarrow 0.344$</td>
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<td></td>
</tr>
<tr>
<td>$\theta_{12}/^\circ$</td>
<td>$33.48^{+0.78}_{-0.75}$</td>
<td>$31.29 \rightarrow 35.91$</td>
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<td></td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.452^{+0.052}_{-0.028}$</td>
<td>$0.382 \rightarrow 0.643$</td>
<td>$0.579^{+0.025}_{-0.037}$</td>
<td>$0.389 \rightarrow 0.644$</td>
<td>$0.385 \rightarrow 0.644$</td>
<td></td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$</td>
<td>$42.3^{+3.0}_{-1.6}$</td>
<td>$38.2 \rightarrow 53.3$</td>
<td>$49.5^{+1.5}_{-2.2}$</td>
<td>$38.6 \rightarrow 53.3$</td>
<td>$38.3 \rightarrow 53.3$</td>
<td></td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>$0.0218^{+0.0010}_{-0.0010}$</td>
<td>$0.0186 \rightarrow 0.0250$</td>
<td>$0.0219^{+0.0011}_{-0.0010}$</td>
<td>$0.0188 \rightarrow 0.0251$</td>
<td>$0.0188 \rightarrow 0.0251$</td>
<td></td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$</td>
<td>$8.50^{+0.20}_{-0.21}$</td>
<td>$7.85 \rightarrow 9.10$</td>
<td>$8.51^{+0.20}_{-0.21}$</td>
<td>$7.87 \rightarrow 9.11$</td>
<td>$7.87 \rightarrow 9.11$</td>
<td></td>
</tr>
<tr>
<td>$\delta_{CP}/^\circ$</td>
<td>$306^{+39}_{-70}$</td>
<td>$0 \rightarrow 360$</td>
<td>$254^{+63}_{-62}$</td>
<td>$0 \rightarrow 360$</td>
<td>$0 \rightarrow 360$</td>
<td></td>
</tr>
<tr>
<td>$\frac{\Delta m^2_{21}}{10^{-5} \text{ eV}^2}$</td>
<td>$7.50^{+0.19}_{-0.17}$</td>
<td>$7.02 \rightarrow 8.09$</td>
<td>$7.50^{+0.19}_{-0.17}$</td>
<td>$7.02 \rightarrow 8.09$</td>
<td>$7.02 \rightarrow 8.09$</td>
<td></td>
</tr>
<tr>
<td>$\frac{\Delta m^2_{3\ell}}{10^{-3} \text{ eV}^2}$</td>
<td>$+2.457^{+0.047}_{-0.047}$</td>
<td>$+2.317 \rightarrow +2.607$</td>
<td>$-2.449^{+0.048}_{-0.047}$</td>
<td>$-2.590 \rightarrow -2.307$</td>
<td>$[+2.325 \rightarrow +2.599]$</td>
<td>$[-2.590 \rightarrow -2.307]$</td>
</tr>
</tbody>
</table>

http://www.nu-fit.org
Propagation in matter

\[ \frac{i}{d} \left( \begin{array}{c} \nu_e \\ \nu_a \end{array} \right) = \mathcal{H} \left( \begin{array}{c} \nu_e \\ \nu_a \end{array} \right) \]

\[ \mathcal{H} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \cdot \begin{pmatrix} 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2F} \end{pmatrix} \cdot \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} + \begin{pmatrix} V_e & 0 \\ 0 & V_a \end{pmatrix} \]

Matter effect

\[ V_e = \sqrt{2} G_F (n_e - n_n/2) \quad V_a = -G_F n_n / \sqrt{2} \]
MSW effect

- Mikheyev Smirnov Wolfenstein effect

\[ E \to 0 : \quad \frac{\Delta m_{21}^2}{2E} \gg V_e - V_\alpha \quad \text{vacuum oscillation limit} \]

\[ E \to \infty : \quad \frac{\Delta m_{21}^2}{2E} \ll V_e - V_\alpha \quad \text{matter effects limit} \]

For solar neutrinos transition takes place in 0.5-7 MeV.
Detection thresholds

Borexino threshold=0.25 MeV

Started data taking in 2007

Liquid scintillator
Does the Low energy solar data fit the MSW prediction?

- Be line measured by Borexino is in complete agreement.

- But there is about 1-2 sigma deviation in data found by Homestake, Borexino (Boron spectrum), SNO-LETA, Super-Kamiokande I and III.

(For a review see, de Holanda and Smirnov, PRD83 (2011) 113011)

Boron Spectrum prediction has a 15 % uncertainty.
Absence of low energy upturn of the spectrum

PHYSICAL REVIEW D 83, 113011 (2011)

\[ \text{Counts / 2 MeV / 345.3 days} \]

\[ \text{Energy (MeV)} \]

\[ \text{8B-neutrinos at Borexino} \]
REDUCING UPTURN

• Superlight Sterile Neutrinos Scenario (SSNS):

• Non-standard interaction:
SSNS

• Superlight sterile neutrinos Scenario (SSNS):
• Not to be confused with warm dark matter candidate or 1 eV sterile neutrino of LSND and MiniBooNE
• De Holanda and Smirnov, PRD 83 (2011) 113611:

\[
\Delta m_{01}^2 = (0.7 - 2) \times 10^{-5} \text{ eV}^2 \quad \sin^2 2\alpha \sim 10^{-3}
\]
SSNS formalism

\[
\begin{pmatrix}
\nu_s \\
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= U \cdot
\begin{pmatrix}
\nu_0 \\
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}

U \equiv
\begin{pmatrix}
1 & 0 \\
0 & U_{\text{PMNS}}
\end{pmatrix} \cdot U_S
\]

\[
U_S =
\begin{pmatrix}
\cos \alpha & \sin \alpha e^{i\delta_1} & 0 & 0 \\
-\sin \alpha e^{-i\delta_1} & \cos \alpha & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\cdot
\begin{pmatrix}
\cos \gamma & 0 & \sin \gamma & 0 \\
0 & 1 & 0 & 0 \\
-\sin \gamma & 0 & \cos \gamma & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\cdot
\begin{pmatrix}
\cos \beta & 0 & 0 & \sin \beta e^{i\delta_2} \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
-\sin \beta e^{-i\delta_2} & 0 & 0 & \cos \beta
\end{pmatrix}
\]

Atmospheric neutrinos for \( \Delta m_{01}^2 \sim 10^{-5} \text{ eV}^2 \):

\[
\sin^2 \beta < 0.2.
\]

Minos bound

\[ \sin^2 \beta \leq 0.2, \quad (90\% \text{ C.L.}). \]

Adomson et al, PRD81 (210) 82004
arXiv:1104.3922
SSNS formalism

\[
\begin{pmatrix}
\nu_s \\
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = U \cdot \begin{pmatrix}
\nu_0 \\
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
U \equiv \begin{pmatrix}
1 & 0 \\
0 & U_{PMNS}
\end{pmatrix} \cdot U_S
\]

\[
U_S = \begin{pmatrix}
\cos \alpha & \sin \alpha e^{-i\delta_1} & 0 & 0 \\
-\sin \alpha e^{i\delta_1} & \cos \alpha & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix} \cdot \begin{pmatrix}
\cos \gamma & 0 & \sin \gamma & 0 \\
0 & 1 & 0 & 0 \\
-\sin \gamma & 0 & \cos \gamma & 0 \\
0 & 0 & 0 & 1
\end{pmatrix} \cdot \begin{pmatrix}
\cos \beta & 0 & 0 & \sin \beta e^{i\delta_2} \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
-\sin \beta e^{-i\delta_2} & 0 & 0 & \cos \beta
\end{pmatrix}
\]

KamLAND and Solar data by 2005 for \(\Delta m_{01}^2 \sim 10^{-5} \text{ eV}^2\):

\[
\sin^2 \alpha < 0.1
\]

Extra relativistic degrees of freedom

\[ \Delta N_{eff} \ll 1 \]

- Mirizzi et al, PLB726 (2013) 8-14

\[ \sin^2 \alpha, \sin^2 \beta, \sin^2 \gamma < \text{few } \times 10^{-2} \]

Effect on solar data

- For \( \Delta m_{01}^2 = (0.7 - 2) \times 10^{-5} \text{ eV}^2 \), \( \sin^2 2\alpha \sim 10^{-3} \)

- Electron neutrino to sterile neutrino conversion

- Dip in survival probability for \( E=0.5-7 \text{ MeV} \)

- Suppression of upturn at lower range energies
Testing SSN

- KamLAND solar, SNO+, ... (De Holanda and Smirnov, PRD 83 (2011) 113611).

- Can we test via reactor experiments?

Medium Baseline reactor experiments

- DAYA BAY in CHINA \(\rightarrow\) JUNO
- RENO in South Korea \(\rightarrow\) RENO-50

Ready for data taking in 2020.

- Baseline \(\sim\) 50 km

\[ \frac{\Delta m^2_{01} L}{2E_\nu} \sim 0.4 \frac{\Delta m^2_{01}}{10^{-5} \text{ eV}^2} \frac{L}{50 \text{ km}} \frac{3 \text{ MeV}}{E_\nu} \]

- Main goal determination of \(\text{sgn}(\Delta m^2_{31})\)
RENO-50 in South Korea
Daya Bay and Juno
Detector characteristics

Liquid Scintillator

- Reno-50: 18 kton, 16.4 GW
- JUNO: 20 kton, 36 GW

Energy resolution $\sim 3\% \sqrt{\frac{E_\nu}{\text{MeV}}}$

- 62 energy bins between 1.8-8MeV
Oscillation in SSNS

- For reactor neutrinos

\[ V_{\text{eff}} \sim G_F n_e \sim G_F n_n \ll \Delta m_{01}^2 / E_\nu < \Delta m_{21}^2 / E_\nu \ll |\Delta m_{31}^2 / E_\nu|. \]

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = |M_0 e^{i\Delta_0} + M_1 e^{i\Delta_1} + M_2 e^{i\Delta_2} + M_3 e^{i\Delta_3}|^2
\]

\[ \Delta_i = m_i^2 L / 2E_\nu \]

\[
M_0 = |\cos \beta (-e^{-i\delta_1} \cos \gamma \cos \theta_{12} \cos \theta_{13} \sin \alpha - \cos \theta_{13} \sin \gamma \sin \theta_{12}) - e^{-i(\delta_D + \delta_2)} \sin \beta \sin \theta_{13}|^2;
\]

\[
M_1 = |\cos \alpha \cos \theta_{12} \cos \theta_{13}|^2
\]

\[
M_2 = |-e^{-i\delta_1} \cos \theta_{12} \cos \theta_{13} \sin \alpha \sin \gamma + \cos \gamma \cos \theta_{13} \sin \theta_{12}|^2
\]

\[
M_3 = |\sin \beta (-e^{-i\delta_1} \cos \gamma \cos \theta_{12} \cos \theta_{13} \sin \alpha - \cos \theta_{13} \sin \gamma \sin \theta_{12}) + e^{-i(\delta_D + \delta_2)} \cos \beta \sin \theta_{13}|^2.
\]
GloBES

Authors:
GLoBES is maintained by Patrick Huber
Joachim Kopp
Manfred Lindner
Walter Winter

http://www.mpi-hd.mpg.de/personalhomes/globes/index.html


Kopp et al, PRD 77
Backgrounds

(i) accidental background;

(ii) $^{13}C(\alpha, n)^{16}O$ background

(iii) Geoneutrino background.

Uncertainties

- We use pull-method to treat uncertainties in neutrino parameters and flux.

- 3% flux uncertainty for JUNO

- 0.3% flux uncertainty for RENO-50

- Gonzalez-Garcia et al, JHEP 12 (2012) 123 (nu-fit.org)

\[ \theta_{12} , \theta_{23} , \Delta m^2_{31} , \Delta m^2_{21} \]
\[ \alpha = \beta = \gamma = 0 \]

The 95\% C.L. upper bound on \( \sin^2 \alpha \) versus \( \Delta m_{01}^2 \).

- Five years of data taking
Case I, $\sin \beta = \sin \gamma = 0$ and $\alpha \neq 0$:

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \left| \cos^2 \theta_{13} \cos^2 \theta_{12} \sin^2 \alpha e^{i\Delta_0} + \cos^2 \alpha \cos^2 \theta_{13} \cos^2 \theta_{12} e^{i\Delta_1} + \cos^2 \theta_{13} \sin^2 \theta_{12} e^{i\Delta_2} + \sin^2 \theta_{13} e^{i\Delta_3} \right|^2
\]

As expected in the $\Delta m_{01}^2 \rightarrow 0$ limit, the sensitivity to $\alpha$ is lost.
Case I, $\sin \beta = \sin \gamma = 0$ and $\alpha \neq 0$:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = |\cos^2 \theta_{13} \cos^2 \theta_{12} \sin^2 \alpha e^{i\Delta_0} + \cos^2 \alpha \cos^2 \theta_{13} \cos^2 \theta_{12} e^{i\Delta_1} + \cos^2 \theta_{13} \sin^2 \theta_{12} e^{i\Delta_2} + \sin^2 \theta_{13} e^{i\Delta_3}|^2$$

- Uncertainty in $\theta_{12}$: $\sin^2 \alpha < \delta \sin^2 \theta_{12} / \cos^2 \theta_{12}$. 
The 95% C.L. upper bound on $\sin^2 \alpha$ versus the baseline.

Five years of data taking with a 20 kton detector and 36 GW reactor source.
\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \left| \cos^2 \theta_{13} \sin^2 \theta_{12} \sin^2 \gamma e^{i\Delta_0} + \cos^2 \theta_{13} \cos^2 \theta_{12} e^{i\Delta_1} + \cos^2 \theta_{13} \sin^2 \theta_{12} \cos^2 \gamma e^{i\Delta_2} + \sin^2 \theta_{13} e^{i\Delta_3} \right|^2 \]
The 95% C.L. upper bound on $\sin^2 \gamma$ versus the baseline.
Case III, $\sin \alpha = \sin \gamma = 0$ and $\beta \neq 0$: In this limit,

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = |\sin^2 \theta_{13} \sin^2 \beta e^{i\Delta_0} + \cos^2 \theta_{13} \cos^2 \theta_{12} e^{i\Delta_1} + \cos^2 \theta_{13} \sin^2 \theta_{12} e^{i\Delta_2} + \sin^2 \theta_{13} \cos^2 \beta e^{i\Delta_3}|^2$$

$$\sin^2 \theta_{13} \ll 1$$
SSNS

- Superlight sterile neutrinos Scenario (SSNS):
- De Holanda and Smirnov, PRD 83 (2011) 113611.

- Parameter range to cure upturn of low energy solar neutrinos:

\[
\Delta m_{01}^2 = (0.7 - 2) \times 10^{-5} \text{ eV}^2 \quad \sin^2 2\alpha \sim 10^{-3}
\]

To probe such small values of mixing about 20 years of data taking is required.
How to improve

- The results are not too sensitive to background, energy resolution, normalization uncertainty of flux and etc

- Accumulation of flux from various reactors are useful

- Main limitation: statistics

- Going to Bigger detector and longer data collecting time smaller values of mixing can be probed.
Conclusion

- The medium baseline reactor experiments can (in principle) probe SSNS
Non-standard Interaction

• Within SM, neutral current interaction are flavor-diagonal and universal.

• But, going to beyond SM

\[ \mathcal{L}_{NSI} = -2\sqrt{2}G_F \epsilon^{fP}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu L \nu_\beta) (\bar{f} \gamma_\mu P f) \]

Examples: Grand unification, various seesaw models, extra U(1), left-right symmetric models, etc
T.Ohlsson, Rept. Prog. Phys 76 (2013) 044201
\[ \mathcal{L}_{NSI} = -2 \sqrt{2} G_F \epsilon_{\alpha \beta}^{fP} (\bar{\nu}_\alpha \gamma^\mu L \nu_\beta) (\bar{f} \gamma_\mu P f) \]

- \( f \) is the matter field (\( u, d \) or \( e \)).
- \( P \) is the chirality projection matrix
- \( \epsilon_{\alpha \beta}^{fP} \) is a dimensionless matrix
Relevant for neutrino oscillation

\[ \mathcal{L}_{NSI} = -2\sqrt{2}G_F \epsilon^f_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu L \nu_\beta)(\bar{f} \gamma_\mu P \ f) \]

\[ \epsilon^f_{\alpha\beta} \equiv \epsilon^f_{\alpha\beta}^L + \epsilon^f_{\alpha\beta}^R. \]
LMA-Dark solution

- For
  \[ |\varepsilon_{ee}^f - \varepsilon_{\mu\mu}^f|, |\varepsilon_{ee}^f - \varepsilon_{\tau\tau}^f| \neq 0 \]

- Another solution with \( \cos(2\theta_{12}) < 0 \)

Miranda et al., JHEP 0610 (2006) 008
Has LMA-dark solution survives?

- Solution survives the test of all the neutrino
  Gonzalez-Garcia and Maltoni, JHEP 1309 (2013) 152
  3 sigma range

Standard Matter Potential

\[
\sin^2 \theta_{12} \in [0.27, 0.35], \\
\sin^2 \theta_{23} \in [0.36, 0.67], \\
\sin^2 \theta_{13} \in [0.016, 0.030], \\
|\Delta m_{31}^2| \in [2.20, 2.58] \times 10^{-3} \text{ eV}^2, \\
\Delta m_{21}^2 \in [6.87, 8.03] \times 10^{-5} \text{ eV}^2.
\]

Generalized Matter Potential

\[
\sin^2 \theta_{12} \in [0.26, 0.35] \oplus [0.65, 0.75], \\
\sin^2 \theta_{23} \in [0.34, 0.67], \\
\sin^2 \theta_{13} \in [0.016, 0.030], \\
|\Delta m_{31}^2| \in [2.20, 2.65] \times 10^{-3} \text{ eV}^2, \\
\Delta m_{21}^2 \in [6.86, 8.10] \times 10^{-5} \text{ eV}^2.
\]
<table>
<thead>
<tr>
<th>Param.</th>
<th>best-fit</th>
<th>90% CL</th>
<th>3σ</th>
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<tbody>
<tr>
<td></td>
<td>LMA</td>
<td>LMA ⊕ LMA-D</td>
<td>LMA</td>
</tr>
<tr>
<td>$\varepsilon_{ee}^{u} - \varepsilon_{\mu\mu}^{u}$</td>
<td>+0.298</td>
<td>[+0.00, +0.51] ⊕ [−1.19, −0.81]</td>
<td>[−0.09, +0.71]</td>
</tr>
<tr>
<td>$\varepsilon_{\tau\tau}^{u} - \varepsilon_{\mu\mu}^{u}$</td>
<td>+0.001</td>
<td>[−0.01, +0.03]</td>
<td>[−0.03, +0.03]</td>
</tr>
<tr>
<td>$\varepsilon_{e\mu}^{u}$</td>
<td>−0.021</td>
<td>[−0.09, +0.04]</td>
<td>[−0.09, +0.10]</td>
</tr>
<tr>
<td>$\varepsilon_{e\tau}^{u}$</td>
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<td>[−0.15, +0.14]</td>
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<tr>
<td>$\varepsilon_{\mu\tau}^{u}$</td>
<td>−0.001</td>
<td>[−0.01, +0.01]</td>
<td>[−0.01, +0.01]</td>
</tr>
<tr>
<td>$\varepsilon_{D}^{u}$</td>
<td>−0.140</td>
<td>[−0.24, −0.01] ⊕ [+0.40, +0.58]</td>
<td>[−0.34, +0.04]</td>
</tr>
<tr>
<td>$\varepsilon_{N}^{u}$</td>
<td>−0.030</td>
<td>[−0.14, +0.13]</td>
<td>[−0.15, +0.13]</td>
</tr>
<tr>
<td>$\varepsilon_{ee}^{d} - \varepsilon_{\mu\mu}^{d}$</td>
<td>+0.310</td>
<td>[+0.02, +0.51] ⊕ [−1.17, −1.03]</td>
<td>[−0.10, +0.71]</td>
</tr>
<tr>
<td>$\varepsilon_{\tau\tau}^{d} - \varepsilon_{\mu\mu}^{d}$</td>
<td>+0.001</td>
<td>[−0.01, +0.03]</td>
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</tr>
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<td>$\varepsilon_{e\mu}^{d}$</td>
<td>−0.023</td>
<td>[−0.09, +0.04]</td>
<td>[−0.09, +0.08]</td>
</tr>
<tr>
<td>$\varepsilon_{e\tau}^{d}$</td>
<td>+0.023</td>
<td>[−0.13, +0.14]</td>
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</tr>
<tr>
<td>$\varepsilon_{\mu\tau}^{d}$</td>
<td>−0.001</td>
<td>[−0.01, +0.01]</td>
<td>[−0.01, +0.01]</td>
</tr>
<tr>
<td>$\varepsilon_{D}^{d}$</td>
<td>−0.145</td>
<td>[−0.25, −0.02] ⊕ [+0.49, +0.57]</td>
<td>[−0.34, +0.05]</td>
</tr>
<tr>
<td>$\varepsilon_{N}^{d}$</td>
<td>−0.036</td>
<td>[−0.14, +0.12]</td>
<td>[−0.14, +0.12]</td>
</tr>
</tbody>
</table>
LMA-Dark

• LMA-Dark solution fits the solar data slightly better as it suppresses the upturn of the spectrum at low energy
Other bounds

- Invisible Z-decay (loop level)
- Neutrino scattering off matter
- Ohlsson, Rept Prog Phys 76 (2013) 44201
Other bounds

- Invisible Z-decay (loop level)
- Neutrino scattering off matter
- Ohlsson, Rept Prog Phys 76 (2013) 44201
- The bound from CHARM scattering experiment combined with NuTeV rules out a part of parameter space for LMA-Dark.

\[
(i.e., \ 0.9 < |\epsilon^{d\mu\mu}_{ee} - \epsilon^{d\mu\mu}_{\mu\mu}| < 0.8 \ at \ 90 \% \ C.L.)
\]

Medium Baseline reactor experiments

- DAYA BAY in CHINA
- RENO in South Korea

Ready for data taking in 2020.

- Baseline ~ 50 km

\[ \frac{\Delta m^2_{01} L}{2E_{\nu}} \sim 0.4 \frac{\Delta m^2_{01}}{10^{-5} \text{ eV}^2} \frac{L}{50 \text{ km}} \frac{3 \text{ MeV}}{E_{\nu}} \]

- Main goal determination of $\text{sgn}(\Delta m^2_{31})$
Charged current NSI

- Charged current NSI

\[
(\bar{d}\gamma^\mu P\ u)(\bar{e}\gamma^\mu L\nu_{\mu(\tau)})
\]

Affects neutrino production and detection

- Neutral current NSI

\[
(\bar{\nu}_\alpha\gamma^\mu L\nu_\beta)(\bar{f}\gamma^\mu P\ f)
\]

Affects neutrino propagation through matter effects
Charged current NSI at JUNO

\[
|\hat{\nu}_\alpha^s\rangle = \frac{1}{N^s_\alpha} \left( |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon^s_{\alpha\beta} |\nu_\beta\rangle \right)
\]

\[
\langle \hat{\nu}_\beta^d \rangle = \frac{1}{N^d_\beta} \left( \langle \nu_\beta | + \sum_{\alpha=e,\mu,\tau} \varepsilon^d_{\alpha\beta} \langle \nu_\alpha | \right)
\]

Khan et al, PRD 88 (2013) 113006
Ohlsson, Zhang and Zhou, PLB 728 (2014) 148
Neutral current NSI at reactor neutrino experiments

\[ \frac{\Delta m^2_{21}}{E_\nu} \gg \sqrt{2}G_F N_e \]

- Small matter effects

- Little sensitivity to neutral current NSI
Our suggestion to test LMA-Dark

- Pouya Bakhti and Y.F., 1403.0744

- Determining $\cos 2\theta_{12}$
Survival probability without matter effects

\[ P(\bar{\nu}_e \to \bar{\nu}_e) = \left| |U_{e1}|^2 + |U_{e2}|^2 e^{i\Delta_{21}} + |U_{e3}|^2 e^{i\Delta_{31}} \right|^2 = \left| c_{12}^2 c_{13}^2 + s_{12}^2 c_{13}^2 e^{i\Delta_{21}} + s_{13}^2 e^{i\Delta_{31}} \right|^2 = \]

\[ c_{13}^4 (1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta_{21}}{2}) + s_{13}^4 + 2s_{13}^2 c_{13}^2 [\cos \Delta_{31} (c_{12}^2 + s_{12}^2 \cos \Delta_{21}) + s_{12}^2 \sin \Delta_{31} \sin \Delta_{21}] \]

where \( \Delta_{ij} = \Delta m_{ij}^2 L/(2E_\nu) \) in which \( L \) is the baseline.
Observation

• A reactor neutrino set-up that is sensitive to hierarchy should also distinguish between solution

\[ \text{with } \theta_{12} > \frac{\pi}{4} \text{ and } \theta_{12} < \frac{\pi}{4} \]
GloBES

Authors:
GLoBES is maintained by Patrick Huber
Joachim Kopp
Manfred Lindner
Walter Winter

http://www.mpi-hd.mpg.de/personalhomes/globes/index.html


Characteristics of JUNO and RENO-50

• The same as before except that we added background caused by $^9\text{Li}$ from cosmic muon interaction

• Grassi, Evslin Giuffoli and Zhang, 1401.7796

• 10000 and 5000 fake neutrinos from Li at JUNO and RENO-50
Energy bins

- Energy range between 1.8 to 8 MeV to 350 bins of 17.7 keV

- Good energy resolution is required

\[ \frac{\delta E_\nu}{E_\nu} \simeq 3\% \times \left( \frac{E_\nu}{\text{MeV}} \right)^{1/2}. \]
Results

• After 5 years of data taking by JUNO and RENO-50

\[ \Delta m_{21}^2 = (7.45 \pm 0.45) \times 10^{-5} \text{ eV}^2 \]

\[ \theta_{13} = (8.75 \pm 0.5) \degree \]
Degeneracy

\[ P(\bar{\nu}_e \to \bar{\nu}_e) = |U_{e1}|^2 + |U_{e2}|^2 e^{i\Delta_{21}} + |U_{e3}|^2 e^{i\Delta_{31}} \leq |c_{12}^2 c_{13}^2 + s_{12}^2 c_{13}^2 e^{i\Delta_{21}} + s_{13}^2 e^{i\Delta_{31}}|^2 \]

\[ s_{12} \leftrightarrow c_{12} \quad (i.e., \theta_{12} \to \frac{\pi}{2} - \theta_{12}) \quad \text{and} \quad \Delta_{31} \to -\Delta_{31} + \Delta_{21} \]
Degeneracy

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = |U_{e1}|^2 + |U_{e2}|^2 e^{i\Delta_{21}} + |U_{e3}|^2 e^{i\Delta_{31}} |^2 = |c_{12}^2 c_{13}^2 + s_{12}^2 c_{13}^2 e^{i\Delta_{21}} + s_{13}^2 e^{i\Delta_{31}} |^2 \]

\[ s_{12} \leftrightarrow c_{12} \]

\[ |s_{12}^2 c_{13}^2 + c_{12}^2 c_{13}^2 e^{i\Delta_{21}} + s_{13}^2 e^{i\Delta_{31}} | = \]

\[ |s_{12}^2 c_{13}^2 + c_{12}^2 c_{13}^2 e^{-i\Delta_{21}} + s_{13}^2 e^{-i\Delta_{31}} | = \]

\[ |e^{i\Delta_{21}} (s_{12}^2 c_{13}^2 + c_{12}^2 c_{13}^2 e^{-i\Delta_{21}} + s_{13}^2 e^{-i\Delta_{31}}) | \]
• As long as we neglect matter effects

\[ s_{12} \leftrightarrow c_{12} \quad (i.e., \, \theta_{12} \rightarrow \frac{\pi}{2} - \theta_{12}) \quad \text{and} \quad \Delta_{31} \rightarrow -\Delta_{31} + \Delta_{21} \]
Summary of results

RENO-50, JUNO and their combined data can discriminate between LMA and LMA-Dark, respectively at >90 % C.L., ~3 sigma C.L. and ~4 sigma C.L. after 5 years and with 3% energy resolution.
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Summary of results

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Summary of results

RENO-50, JUNO and their combined data can discriminate between LMA and LMA-Dark, respectively at >90 % C.L., ~3 sigma C.L. and ~4 sigma C.L. after 5 years and with 3% energy resolution.

- Increasing energy resolution from 3% to 3.5% makes the wrong solution acceptable at 3 sigma!
- Removing the background, JUNO alone can rule the wrong solution at more than 3 sigma.
- There is a degeneracy that can be solved by scattering experiments sensitive to NSI.
Backup

- Gadolinium-doped Liquid scintillator
- AD=anti-neutrino detector:
- Accidental background: correlation of two unrelated events
- Beta-neutron decay of Li/He produced by muons inside AD
- Neutron spallation
\[ H = V_{vac} + V_{eff} \quad \text{where} \quad V_{vac} = U_{PMNS} \cdot \text{Diag}(\Delta_1, \Delta_2, \Delta_3) \cdot U_{PMNS}^T, \]

\[ \Delta_i = m_i^2 / (2E_\nu) \]

Replacing \( \theta_{12} \to \pi / 2 - \theta_{12}, \delta \to \delta + \pi \) and \( \Delta_1 \leftrightarrow \Delta_2, \)

\[ V_{vac} \text{ will transform into } S \cdot V_{vac} \cdot S \]

\[ S = \text{Diag}(1, -1, -1) \]
Since we have the freedom of rephasing $\nu_\alpha$

- The oscillation probability will remain the same if

\[ V_{eff} \rightarrow S \cdot V_{eff} \cdot S; \]

$\Delta_1 \leftrightarrow \Delta_2$ is equivalent to $\Delta_{21} \rightarrow -\Delta_{21}$ and $\Delta_{31} \rightarrow \Delta_{31} - \Delta_{21}$
Invariance of probabilities under

\[ \theta_{12} \to \frac{\pi}{2} - \theta_{12}, \quad \delta \to \pi - \delta, \quad \Delta_{31} \to -\Delta_{13} + \Delta_{21} \quad \text{and} \quad V_{eff} \to -S \cdot V_{eff} \cdot S. \]
\[ V_{eff} \rightarrow -S \cdot V_{eff} \cdot S \]

\[ \varepsilon_{ee} + 1 \rightarrow -(1 + \varepsilon_{ee}). \]
\[ \epsilon_{\alpha\beta} = Y_u \epsilon_{\alpha\beta}^u + Y_d \epsilon_{\alpha\beta}^d \]

\[ Y_u = 2 + Y_n \text{ and } Y_d = 1 + 2Y_n \]

- Composition of the sun and the earth are different so degeneracy can be partially solved.
We examined the possibility of solving degeneracy by using the NOvA experiment. Sensitivity of NOvA to NSI had also been discussed in [34]. We used the GLoBES software to carry out the analysis. Details of the simulation of NOvA experiment is based on [35, 36]. For true values we have taken $\theta_{12} = 33.57$ and set all the NSI parameters to zero; $\epsilon = 0$. We have assumed normal hierarchical scheme. We have found that after six years of data taking (i.e., 3 years in neutrino mode and 3 years in antineutrino mode), NOvA can rule out the other solution with opposite sign of $\cos 2\theta_{12}$ and $\Delta_{31}$ with $\chi^2 = 3.9$ which for 2 dof corresponds to about 85% C.L.
Solution of the puzzle

- Neutrino oscillation
- Pontecorvo proposed in 1957 in analogy of

\[ K^0 \iff \bar{K}^0 \]

Even before solar neutrinos were discovered!!!
Invisible Z decay width

\[ Z \rightarrow e^- e^+ \quad Z \rightarrow \mu^- \mu^+ \]

\[ Z \rightarrow \nu_e \bar{\nu}_e, \nu_\mu \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\tau \]

Fourth Neutrino ?!
arXiv:1307.3922