A REVIEW ON THE PRESENT STATUS OF NEUTRINO MIXING AND OSCILLATIONS

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Neutrino Oscillations

- Neutrino Oscillations are Flavor Transitions which oscillate with distance.

- Flavor Neutrinos: \( \nu_e, \nu_\mu, \nu_\tau \) produced in Weak Interactions

- Massive Neutrinos: \( \nu_1, \nu_2, \nu_3 \) propagate from Source to Detector

- A Flavor Neutrino is a superposition of Massive Neutrinos

\[
\begin{align*}
|\nu_e\rangle &= U_{e1} |\nu_1\rangle + U_{e2} |\nu_2\rangle + U_{e3} |\nu_3\rangle \\
|\nu_\mu\rangle &= U_{\mu1} |\nu_1\rangle + U_{\mu2} |\nu_2\rangle + U_{\mu3} |\nu_3\rangle \\
|\nu_\tau\rangle &= U_{\tau1} |\nu_1\rangle + U_{\tau2} |\nu_2\rangle + U_{\tau3} |\nu_3\rangle 
\end{align*}
\]

- \( U \) is the 3 × 3 Neutrino Mixing Matrix
\[ |\nu(t = 0)\rangle = |\nu_\mu\rangle = U_{\mu 1} |\nu_1\rangle + U_{\mu 2} |\nu_2\rangle + U_{\mu 3} |\nu_3\rangle \]

\[ |\nu(t > 0)\rangle = U_{\mu 1} e^{-iE_1 t} |\nu_1\rangle + U_{\mu 2} e^{-iE_2 t} |\nu_2\rangle + U_{\mu 3} e^{-iE_3 t} |\nu_3\rangle \neq |\nu_\mu\rangle \]

\[ E_k^2 = p^2 + m_k^2 \]

\[ P_{\nu_\mu \rightarrow \nu_e}(t > 0) = |\langle \nu_e | \nu(t > 0) \rangle|^2 \propto \sin^2 \left( \frac{\Delta m_{kj}^2 L}{4 E} \right) \]

Neutrino Oscillations are Flavor Transitions

\[ \begin{align*}
\nu_e &\rightarrow \nu_\mu \\
\bar{\nu}_e &\rightarrow \bar{\nu}_\mu \\
\nu_e &\rightarrow \nu_\tau \\
\bar{\nu}_e &\rightarrow \bar{\nu}_\tau \\
\nu_\mu &\rightarrow \nu_e \\
\bar{\nu}_\mu &\rightarrow \bar{\nu}_e \\
\nu_\mu &\rightarrow \nu_\tau \\
\bar{\nu}_\mu &\rightarrow \bar{\nu}_\tau
\end{align*} \]

transition probabilities depend on \( U \) and \( \Delta m_{kj}^2 \equiv m_k^2 - m_j^2 \)
Three-Neutrino Mixing Paradigm

Standard Parameterization of Mixing Matrix

\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix} \]

\[ c_{ab} \equiv \cos \theta_{ab} \quad s_{ab} \equiv \sin \theta_{ab} \quad 0 \leq \theta_{ab} \leq \frac{\pi}{2} \quad 0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi \]

OSCILLATION PARAMETERS

\{ \begin{align*} &3 \text{ Mixing Angles: } \theta_{12}, \theta_{23}, \theta_{13} \\
&1 \text{ CPV Dirac Phase: } \delta_{13} \\
&2 \text{ independent } \Delta m_{kj}^2 \equiv m_k^2 - m_j^2: \Delta m_{21}^2, \Delta m_{31}^2 \\
&2 \text{ CPV Majorana Phases: } \lambda_{21}, \lambda_{31} \iff |\Delta L| = 2 \text{ processes} \end{align*} \}
Experimental Evidences of Neutrino Oscillations

\[ \Delta m^2_S = \Delta m^2_{21} \approx 7.6 \times 10^{-5} \text{ eV}^2 \]
\[ \sin^2 \vartheta_S = \sin^2 \vartheta_{12} \approx 0.30 \]

\[ \Delta m^2_A = |\Delta m^2_{31}| \approx 2.4 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 \vartheta_A = \sin^2 \vartheta_{23} \approx 0.50 \]

\[ \Delta m^2_A = |\Delta m^2_{31}| \]
\[ \sin^2 \vartheta_{13} \approx 0.023 \]
Recent Experimental Results

- OPERA observed a fifth $\nu_\tau$ candidate event: $5\sigma$ evidence of long-baseline $\nu_\mu \rightarrow \nu_\tau$ transitions!
  arXiv:1507.01417

- NO$\nu$A observed first long-baseline neutrino events:
  $\nu_\mu$ disappearance (33 $\nu_\mu$ events vs 201 without oscillations)
  and
  $\nu_e$ appearance (6 $\nu_e$ events with 1 background).
  7 August 2015 Press Release
\[ E \approx 3.6 \text{MeV} \text{ (reactor } \bar{\nu}_e \text{)} \]

\[
\frac{E}{L} \approx \Delta m_A^2 \\
\frac{E}{L} \approx \Delta m_S^2
\]

JUNO
RENO-50
KamLAND

\[ P_{\nu_e \rightarrow \nu_e} \]

\[ L \text{ [km]} \]

$10^{-1}$ $1$ $10$ $10^2$ $10^3$
Recent Global Fits

- Capozzi, Fogli, Lisi, Marrone, Montanino, Palazzo  
  Status of three-neutrino oscillation parameters, circa 2013  

- Forero, Tortola, Valle  
  Neutrino oscillations refitted  

- Gonzalez-Garcia, Maltoni, Schwetz  
  Updated fit to three neutrino mixing: status of leptonic CP violation  

- Bergstrom, Gonzalez-Garcia, Maltoni, Schwetz  
  Bayesian global analysis of neutrino oscillation data  
  arXiv:1507.04366
\( \Delta m_S^2 = \Delta m_{21}^2 \approx 7.5 \pm 0.3 \times 10^{-5} \text{ eV}^2 \) uncertainty \( \approx 3\% \)

\( \Delta m_A^2 = |\Delta m_{31}^2| \approx |\Delta m_{32}^2| \approx 2.4 \pm 0.1 \times 10^{-3} \text{ eV}^2 \) uncertainty \( \approx 4\% \)

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta_{13}} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i\lambda_{21}} & 0 \\
0 & 0 & e^{i\lambda_{31}}
\end{pmatrix}
\]

\( \vartheta_{23} = \vartheta_A \)
\( \sin^2 \vartheta_{23} \approx 0.4 - 0.6 \)

\( P_{\text{osc}} \propto \sin^2 2\vartheta_{23} \)

maximal and flat

at \( \vartheta_{23} = 45^\circ \)

Daya Bay, RENO

Double Chooz

T2K, MINOS

\( \sin^2 \vartheta_{12} \approx 0.30 \pm 0.01 \)

\( \sin^2 \vartheta_{13} \approx 0.023 \pm 0.002 \)

\( \delta_{13} \approx 3\pi/2? \)

\( \frac{\delta \sin^2 \vartheta_{23}}{\sin^2 \vartheta_{23}} \approx 40\% \)

\( \frac{\delta \sin^2 \vartheta_{13}}{\sin^2 \vartheta_{13}} \approx 10\% \)

\( \frac{\delta \sin^2 \vartheta_{12}}{\sin^2 \vartheta_{12}} \approx 5\% \)
Maximal CP Violation?

\[
\theta (\sin^{2} \theta_{13}, \delta_{\text{CP}}/\pi)\]

T2K Only 68% Credible Region
T2K Only 90% Credible Region
T2K+Reactor 68% Credible Region
T2K+Reactor 90% Credible Region
T2K+Reactor Best Fit Point
T2K Only Best Fit Line

Mass Ordering

\[ \Delta m^2 \]

\[ \nu_e \quad \nu_\mu \quad \nu_\tau \]

\[ m^2 \]

Normal Ordering

\[ \Delta m_{31}^2 > \Delta m_{32}^2 > 0 \]

Inverted Ordering

\[ \Delta m_{32}^2 < \Delta m_{31}^2 < 0 \]

absolute scale is not determined by neutrino oscillation data
Determination of Mass Ordering

1. Matter Effects: Atmospheric (PINGU, ORCA), Long-Baseline, Supernova Experiments

   ▶ $\nu_e \leftrightarrow \nu_\mu$ MSW resonance: $V = \frac{\Delta m_{13}^2 \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m_{13}^2 > 0$ NO

   ▶ $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ MSW resonance: $V = -\frac{\Delta m_{13}^2 \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m_{13}^2 < 0$ IO

2. Phase Difference: Reactor $\bar{\nu}_e \rightarrow \bar{\nu}_e$ (JUNO, RENO-50)

 Normal Ordering

<table>
<thead>
<tr>
<th>$\Delta m_{31}^2$</th>
<th>$\Delta m_{32}^2$</th>
<th>$\Delta m_{21}^2$</th>
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<tbody>
<tr>
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<td>\Delta m_{31}^2</td>
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 Inverted Ordering

<table>
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</tbody>
</table>
$$P_{\nu_e \rightarrow \nu_e}^{(-)} = 1 - \cos^4 \vartheta_{13} \sin^2 2\vartheta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E} \right) - \cos^2 \vartheta_{12} \sin^2 2\vartheta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) - \sin^2 \vartheta_{12} \sin^2 2\vartheta_{13} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)$$

Open Problems

- $\theta_{23} \lesssim 45^\circ$ ?
  - T2K (Japan), NO$\nu$A (USA), PINGU (Antarctica), ORCA (EU), INO (India), . . .

- Mass Ordering (Hierarchy) ?
  - NO$\nu$A (USA), JUNO (China), RENO-50 (Korea), PINGU (Antarctica), ORCA (EU), INO (India), . . .

- CP violation ? $\delta_{13} \approx 3\pi/2$ ?
  - T2K (Japan), NO$\nu$A (USA), DUNE (USA), HyperK (Japan), . . .

- Absolute Mass Scale ?
  - $\beta$ Decay, Neutrinoless Double-$\beta$ Decay, Cosmology, . . .

- Dirac or Majorana ?
  - Neutrinoless Double-$\beta$ Decay, . . .

- Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?
Absolute Scale of Neutrino Masses

Lightest mass: \( m_1, m_2, m_3 \) [eV]

\[
egin{align*}
m_2 &= m_1 + \Delta m_{21} = m_1 + \Delta m_S^2 \\
m_3 &= m_1 + \Delta m_{31} = m_1 + \Delta m_A^2
\end{align*}
\]

Quasi-Degenerate for \( m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gtrsim \sqrt{\Delta m_A^2} \simeq 5 \times 10^{-2} \text{ eV} \)

95% Cosmological Limit: Planck TT + lowP + BAO [arXiv:1502.01589]
Neutrino Masses in $\beta$ decay

\[ m_{\beta}^2 = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2 \]

- Quasi-Degenerate:
  \[ m_{\beta}^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2 \]

- Inverted Hierarchy:
  \[ m_{\beta}^2 \simeq (1 - s_{13}^2) \Delta m_A^2 \simeq \Delta m_A^2 \]

- Normal Hierarchy:
  \[ m_{\beta}^2 \simeq s_{12}^2 c_{13}^2 \Delta m_S^2 + s_{13}^2 \Delta m_A^2 \simeq 2 \times 10^{-5} + 6 \times 10^{-5} \text{eV}^2 \]

\[ m_\beta \lesssim 4 \times 10^{-2} \text{eV} \]

↓ Normal Spectrum
Neutrinoless Double-β Decay

\[ \Delta L = 2 \]
\[ \mathcal{N}(A, Z) \rightarrow \mathcal{N}(A, Z + 2) + e^- + e^- \]
\[ (T_{1/2}^{0\nu})^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 |m_{\beta\beta}|^2 \]

\[ m_{\beta\beta} = \sum_k U_{ek}^2 m_k \]

Effective Majorana Neutrino Mass

\[ m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3 \]

\[ \alpha_{21} = 2\lambda_{21} \quad \alpha_{31} = 2(\lambda_{31} - \delta_{13}) \]

possible cancellations between the three mass contributions
Indications of SBL Oscillations Beyond $3\nu$
Reactor Electron Antineutrino Anomaly


New reactor $\bar{\nu}_e$ fluxes


$R = N_{\text{exp}} / N_{\text{no osc.}}$

$R = 0.933 \pm 0.021$

$L \sim 10 - 100 \text{ m}$

$E \sim 4 \text{ MeV}$

Nominal $\approx 3.1\sigma$ deficit

$\Delta m^2 \gtrsim 0.5 \text{ eV}^2$

($\gg \Delta m^2_A \gg \Delta m^2_S$)

Problem: unknown $\bar{\nu}_e$ flux uncertainties?

[Hayes, Friar, Garvey, Jonkmans, PRL 112 (2014) 202501; Dwyer, Langford, PRL 114 (2015) 012502]
$E \approx 3.6\text{MeV (reactor } \bar{\nu}_e)\)$
Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

Detection Process: \(\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-\)

\(\nu_e\) Sources: \(e^- + {}^{51}\text{Cr} \rightarrow {}^{51}\text{V} + \nu_e\) \(e^- + {}^{37}\text{Ar} \rightarrow {}^{37}\text{Cl} + \nu_e\)

\(\bar{\nu}_e \rightarrow \bar{\nu}_e\) \(E \sim 0.7\) MeV

\(\langle L \rangle_{\text{GALLEX}} = 1.9\) m

\(\langle L \rangle_{\text{SAGE}} = 0.6\) m

Nominal \(\approx 2.9\sigma\) anomaly

\(\Delta m^2 \gtrsim 1\) eV\(^2\) \((\gg \Delta m_A^2 \gg \Delta m_S^2)\)

\[
R = \frac{N_{\text{exp}}}{N_{\text{no osc.}}}
\]

\(R = 0.84 \pm 0.05\)


\(\text{[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807]}\)

\text{MPLA 22 (2007) 2499; PRD 78 (2008) 073009;}
\text{PRC 83 (2011) 065504]}\)

\(\text{[Mention et al, PRD 83 (2011) 073006]}\)

\(\triangleright {}^3\text{He} + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + {}^3\text{H}\) cross section measurement \([\text{Frekers et al., PLB 706 (2011) 134]}\)

\(\triangleright E_{\text{th}}(\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-) = 233.5 \pm 1.2\) keV \([\text{Frekers et al., PLB 722 (2013) 233]}\)
\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \quad L \simeq 30 \text{ m} \quad 20 \text{ MeV} \leq E \leq 60 \text{ MeV} \]

- Well known source of \( \bar{\nu}_\mu \):
  \[ \mu^+ \text{ at rest} \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]

- \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \quad L \simeq 30 \text{ m} \)

- Well known detection process of \( \bar{\nu}_e \):
  \[ \bar{\nu}_e + p \rightarrow n + e^+ \]

- But signal not seen by KARMEN with same method at \( L \simeq 18 \text{ m} \)

Nominal \( \approx 3.8\sigma \) excess \quad \Delta m^2 \gtrsim 0.2 \text{ eV}^2 \quad (\gg \Delta m^2_A \gg \Delta m^2_S)
MiniBooNE

\[ L \simeq 541 \text{ m} \quad \text{200 MeV} \leq E \lesssim 3 \text{ GeV} \]

\[ \nu_\mu \rightarrow \nu_e \quad \text{[PRL 102 (2009) 101802]} \]

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \quad \text{[PRL 110 (2013) 161801]} \]

- Purpose: check LSND signal.
- Different \( L \) and \( E \).
- Similar \( L/E \) (oscillations).
- No money, no Near Detector.

- LSND signal: \( E > 475 \text{ MeV} \).
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!
Effective SBL Oscillation Probabilities in 3+1 Schemes

\[ \begin{align*}
P_{\nu_{\alpha} \rightarrow \nu_{\beta}}^{SBL} & \approx \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \\
P_{\nu_{\alpha} \rightarrow \nu_{\alpha}}^{SBL} & \approx 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \\
\end{align*} \]

\[ \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha4}|^2 |U_{\beta4}|^2 \]

\[ \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha4}|^2 \left( 1 - |U_{\alpha4}|^2 \right) \]

Perturbation of 3ν Mixing:  
\[ |U_{e4}|^2 \ll 1, \ |U_{\mu4}|^2 \ll 1, \ |U_{\tau4}|^2 \ll 1, \ |U_{s4}|^2 \approx 1 \]

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases
- But CP violation is not observable in current SBL experiments!

- Observable in LBL accelerator exp. sensitive to \( \Delta m_{\text{ATM}}^2 \) [de Gouvea, Kelly, Kobach, PRD 91 (2015) 053005; Klop, Palazzo, PRD 91 (2015) 073017; Berryman, de Gouvea, Kelly, Kobach, arXiv:1507.03986] and solar exp. sensitive to \( \Delta m_{\text{SOL}}^2 \) [Long, Li, Giunti, PRD 87, 113004 (2013) 113004]
3+1: Appearance vs Disappearance

- Amplitude of $\nu_e$ disappearance:

  $$\sin^2 2\theta_{ee} = 4|U_{e4}|^2 (1 - |U_{e4}|^2) \approx 4|U_{e4}|^2$$

- Amplitude of $\nu_\mu$ disappearance:

  $$\sin^2 2\theta_{\mu\mu} = 4|U_{\mu4}|^2 (1 - |U_{\mu4}|^2) \approx 4|U_{\mu4}|^2$$

- Amplitude of $\nu_\mu \rightarrow \nu_e$ transitions:

  $$\sin^2 2\theta_{e\mu} = 4|U_{e4}|^2 |U_{\mu4}|^2 \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

- Upper bounds on $\nu_e$ and $\nu_\mu$ disappearance $\Rightarrow$ strong limit on $\nu_\mu \rightarrow \nu_e$


- Similar constraint in $3+2$, $3+3$, . . . , $3+N_s$!

Pragmatic Global 3+1 Fit


- **APP** $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$: LSND ($\nu_s$), MiniBooNE (?), OPERA ($\nu_s$), ICARUS ($\nu_s$), KARMEN ($\nu_s$), NOMAD ($\nu_s$), BNL-E776 ($\nu_s$)
- **DIS** $\nu_e$ & $\bar{\nu}_e$: Reactors ($\nu_s$), Gallium ($\nu_s$), $\nu_e$C ($\nu_s$), Solar ($\nu_s$)
- **DIS** $\nu_\mu$ & $\bar{\nu}_\mu$: CDHSW ($\nu_s$), MINOS ($\nu_s$), Atmospheric ($\nu_s$), MiniBooNE/SciBooNE ($\nu_s$)

No Osc. nominally disfavored at $\approx 6.3\sigma$

$\Delta \chi^2$/NDF = 47.7/3

MiniBooNE $E > 475$ MeV

GoF = 26%  PGoF = 7%
$\nu_e$ and $\nu_\mu$ Disappearance
Neutrinoless Double-$\beta$ Decay

\[ m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3 + |U_{e4}|^2 e^{i\alpha_{41}} m_4 \]

\[ m_{\beta\beta}^{(k)} = |U_{ek}|^2 m_k \]

\[ m_{\beta\beta}^{(4)} \approx |U_{e4}|^2 \sqrt{\Delta m_{41}^2} \]

surprise:
possible cancellation
with \( m_{\beta\beta}^{(3\nu)} \)

[Barry et al, JHEP 07 (2011) 091]
[Li, Liu, PLB 706 (2012) 406]
[Rodejohann, JPG 39 (2012) 124008]
[Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]
| $U_{e1}$ | $2\,m_1$ | $10^{-4}$ | $10^{-3}$ | $10^{-2}$ | $10^{-1}$ | $10^{1}$ |
| $U_{e2}$ | $2\,m_2$ | $10^{-4}$ | $10^{-3}$ | $10^{-2}$ | $10^{-1}$ | $10^{1}$ |
| $U_{e3}$ | $2\,m_3$ | $10^{-4}$ | $10^{-3}$ | $10^{-2}$ | $10^{-1}$ | $10^{1}$ |

Lightest mass: $m_1$ [eV]

| $m_{\beta\beta}$ | $[eV]$ |
| $10^{-4}$ | $10^{-3}$ | $10^{-2}$ | $10^{-1}$ | $10^{1}$ |

Inverted 3ν Ordering

$\sigma^1$: $(+,+,+)$
$\sigma^2$: $(+,+,−)$
$\sigma^3$: $(+,−,+)$
$\sigma^4$: $(+,−,−)$
$\sigma^5$: $(−,+,+)$
$\sigma^6$: $(−,+,−)$
$\sigma^7$: $(−,−,+)$
$\sigma^8$: $(−,−,−)$

Normal 3ν Ordering

$\sigma^1$: $(+,+,+)$
$\sigma^2$: $(+,+,−)$
$\sigma^3$: $(+,−,+)$
$\sigma^4$: $(+,−,−)$
$\sigma^5$: $(−,+,+)$
$\sigma^6$: $(−,+,−)$
$\sigma^7$: $(−,−,+)$
$\sigma^8$: $(−,−,−)$

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Normal 3ν Ordering – 3σ

\[ m_\beta \ [eV] \]

\[ |m_{\beta\beta}| \ [eV] \]

\[ \Sigma \ [eV] \]

Inverted 3ν Ordering – 3σ

\[ m_\beta \ [eV] \]

\[ |m_{\beta\beta}| \ [eV] \]

\[ \Sigma \ [eV] \]

Robust Three-Neutrino Mixing Paradigm.

Open problems with exciting experimental program: $\theta_{23} \lesssim 45^\circ$?, Mass Ordering, CP Violation, Absolute Mass Scale, Dirac or Majorana?

Determination of Mass Ordering is very important!

Short-Baseline $\nu_e$ and $\bar{\nu}_e$ Disappearance:

- Experimental data agree on Reactor $\bar{\nu}_e$ and Gallium $\nu_e$ anomalies.
- Problem: unknown systematic uncertainties (Reactor $\bar{\nu}_e$ flux).
- Many promising projects to test unambiguously short-baseline $\nu_e$ and $\bar{\nu}_e$ disappearance in a few years with reactors and radioactive sources.
- Independent tests through effect of $m_4$ in $\beta$-decay and $\beta\beta_{0\nu}$-decay.

Short-Baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ LSND Signal:

- Not seen by other SBL $^{(-)}\nu_\mu \to ^{(−)}\nu_e$ experiments.
- MiniBooNE experiment has been inconclusive.
- Experiments with near detector are needed to check LSND signal!

Pragmatic 3+1 Fit is fine: moderate APP-DIS tension.

Light Sterile Neutrinos in Cosmology: see S. Gariazzo talk.
Backup Slides
Global 3+1 Fit

Our Fit

Kopp, Machado, Maltoni, Schwetz

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

$\sin^2 2\theta_{\text{e}\mu}$

GoF = 5%
PGoF = 0.1%


Kopp, Machado, Maltoni, Schwetz

$\Delta m^2$

$\sin^2 2\theta_{\mu e}$

90%, 99%, 99.73% CL, 2 dof

disappearance

appearance

GoF = 19%
PGoF = 0.01%

[Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]
MiniBooNE Low-Energy Excess?

No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 3 \times 10^{-3}$

Neutrino energy reconstruction problem? [Martini, Ericson, Chanfray, PRD 87 (2013) 013009]

MB low-energy excess is the main cause of bad APP-DIS $\text{PGoF} = 0.1\%$

Pragmatic Approach: discard the Low-Energy Excess because it is very likely not due to oscillations