# Texture Zero in Neutrino Mass Matrices

*Confronted with Experimental Data from JUNO*


Marek Michalczyk

University of Silesia in Katowice
Institute of Physics
Particle Physics Theory and Phenomenology Group


**1st Annual MAPS Meeting**

*"Bridging Theory and Experiments: Pushing the Boundaries of Neutrino Oscillation Precision Physics"*

Ruđer Bošković Institute, Zagreb
1 July 2026

UNIVERSITY OF SILESIA IN KATOWICE

HRZZ Croatian Science Foundation

Swiss National Science Foundation

NATIONAL SCIENCE CENTRE POLAND

# Leptons and Flavor States

Leptons are divided into three generations, each consisting of a charged particle and its corresponding neutrino.

| Generation | Charged Lepton | Neutrino Flavor |
|---|---|---|
| I | Electron ($e$) | Electron Neutrino ($\nu_e$) |
| II | Muon ($\mu$) | Muon Neutrino ($\nu_\mu$) |
| III | Tau ($\tau$) | Tau Neutrino ($\nu_\tau$) |

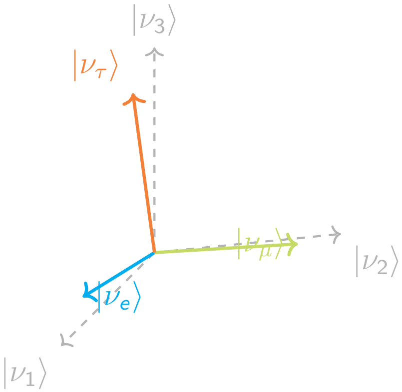
**Flavor Eigenstates:** produced in weak interactions as

$$|\nu_e\rangle, \quad |\nu_\mu\rangle, \quad |\nu_\tau\rangle$$

Flavor states are quantum superpositions of mass eigenstates.

**Matrix Representation:**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$




**Summation Notation:**

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} \, |\nu_i\rangle$$

$\alpha \in \{e, \mu, \tau\}$ — flavor index
$i \in \{1, 2, 3\}$ — mass index

# Neutrino Mass Hierarchy

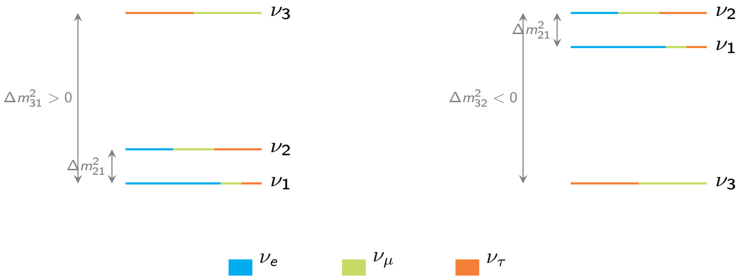
Oscillation experiments measure $\Delta m^2$, leaving two possible orderings.

**Normal Hierarchy (NH)**

$m_1 < m_2 \ll m_3$

**Inverted Hierarchy (IH)**

$m_3 \ll m_1 < m_2$

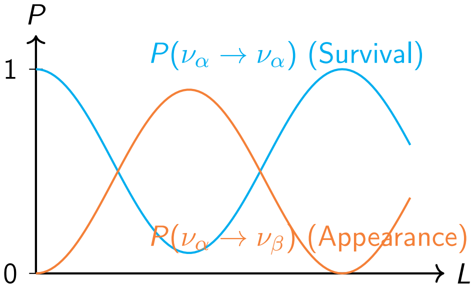


**2-Flavor Approximation:**

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

**Variables:**
$\theta$ – mixing angle
$\Delta m^2$ – mass splitting [$eV^2$]
$L$ – baseline distance [km]
$E$ – neutrino energy [GeV]

*Note: The factor 1.27 comes from putting $\hbar c$ and unit conversions into the formula.*



1. **Mass Term in Lagrangian**

$$-\mathcal{L}_D = \overline{\nu_{iL}}(M_D)_{ij}\nu_{jR} + \text{h.c.}$$

2. **Full Matrix Form (Complex, No Symmetry)**

$$M_D = \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{\mu e} & m_{\mu\mu} & m_{\mu\tau} \\ m_{\tau e} & m_{\tau\mu} & m_{\tau\tau} \end{pmatrix}$$

3. **Diagonalization (Bi-unitary)**

Requires two independent unitary matrices ($V_L$ and $V_R$):

$$V_L^\dagger M_D V_R = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

# Neutrino Mass: Hermitian Dirac Matrix

**1. Mass Term in Lagrangian**

$$-\mathcal{L}_D = \overline{\nu_{iL}}(M_D)_{ij}\nu_{jR} + \text{h.c.}$$

**2. Full Matrix Form (Hermitian: $M_D = M_D^\dagger$)**
Diagonal elements are strictly real ($m_{ee}, m_{\mu\mu}, m_{\tau\tau} \in \mathbb{R}$):

$$M_D = \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{e\mu}^* & m_{\mu\mu} & m_{\mu\tau} \\ m_{e\tau}^* & m_{\mu\tau}^* & m_{\tau\tau} \end{pmatrix}$$

**3. Diagonalization (Unitary)**
Requires a single unitary matrix ($U$):

$$U^\dagger M_D U = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

1. **Mass Term in Lagrangian**

$$-\mathcal{L}_M = \frac{1}{2}\overline{\nu^c_{iL}}(M_M)_{ij}\nu_{jL} + \text{h.c.}$$

2. **Full Matrix Form (Symmetric: $M_M = M_M^T$)**

$$M_M = \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{e\mu} & m_{\mu\mu} & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & m_{\tau\tau} \end{pmatrix}$$

3. **Diagonalization**

Requires a transpose instead of a Hermitian conjugate ($U^T$):

$$U^T M_M U = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

## The PMNS matrix is a product of three fundamental rotations

Operates sequentially from right (solar sector) to left (atmospheric sector).

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\substack{\textbf{Atmospheric} \\ (\nu_\mu \leftrightarrow \nu_\tau)}} \times \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\substack{\textbf{Reactor \& CP} \\ (\nu_e \leftrightarrow \nu_\tau)}} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\textbf{Solar} \\ (\nu_e \leftrightarrow \nu_\mu)}}$$

The resulting **Dirac Matrix** (governing all oscillations) is the combined product:

$$U_{\text{Dirac}} = R_{23} \times R_{13}(\delta) \times R_{12}$$

# PMNS Parameters & Majorana Phases

The full PMNS matrix separates into Dirac mixing and Majorana phases:

$$U_{\text{PMNS}} = U_{\text{Dirac}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}}_{\text{Majorana Phases}}$$

## Oscillation Parameters

(6 independent parameters)

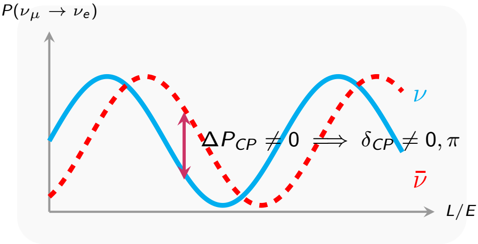
- **3 Mixing Angles:** $\theta_{12}, \theta_{23}, \theta_{13}$
- **2 Mass Splittings:** $\Delta m^2_{21}, \Delta m^2_{31}$
- **1 Dirac CP Phase:** $\delta_{CP}$

**Expanded Dirac Matrix ($U_{\text{Dirac}}$):**

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix}$$

Majorana phases ($\alpha_{21}, \alpha_{31}$) are strictly **invisible** to standard oscillation experiments. They only appear in lepton-number violating processes (e.g., $0\nu\beta\beta$).

# CP Violation: The $\delta_{CP}$ Phase




$$\Delta P_{CP} = P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) \propto \sin \delta_{CP}$$

- **Asymmetry:** $\delta_{CP}$ drives the oscillation split between $\nu$ and $\bar{\nu}$.
- **Texture Zero Role:** Constrains the parameter space, mathematically interlocking $\delta_{CP}$ with the measured mixing angles.

## Precision improvement in the Solar Sector

| Parameter | NuFIT 6.0 (Before) | NuFIT 6.1 (Updated) |
|---|---|---|
| $\theta_{12}/^\circ$ | $33.68^{+0.73}_{-0.70}$ | $33.76^{+0.42}_{-0.41}$ |
| $\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$ | $7.49^{+0.19}_{-0.19}$ | $7.537^{+0.094}_{-0.100}$ |

*Notice how the uncertainties for the solar parameters ($\theta_{12}$ and $\Delta m^2_{21}$) have shrunk by roughly a half! This is exactly where new precision data makes a massive impact.*

# JUNO: Experimental Layout & Geometry

| Specification | Design Value | Physics Purpose |
|---|---|---|
| **Baseline** | $\sim$53 km from reactors | Sweet spot for $\theta_{12}$ and $\Delta m^2_{21}$ oscillations |
| **Overburden** | $\sim$700 m of granite | Muon cosmic background reduction ($\sim 10^5$ times) |
| **Target Mass** | 20 kilotons | High statistics for rare neutrino events |
| **Energy Resolution** | $< 3\%/\sqrt{E}$ [MeV] | Resolving sub-percent mass hierarchy peaks |

*Data sources: "Neutrino Physics with JUNO", arXiv:1507.05613; "JUNO Physics and Detector", arXiv:2104.02565*

# JUNO: Detector Technology & Dual PMT System

- **Central Detector (CD):** 35.4m acrylic sphere; 20 kt Liquid Scintillator.
- **Dual PMT System:** **17.6k** Large (20") & **25.6k** Small (3") tubes for sub-percent energy resolution.
- **Water Cherenkov Veto:** 35 kt pure water shield with 2.4k PMTs to tag cosmic rays.

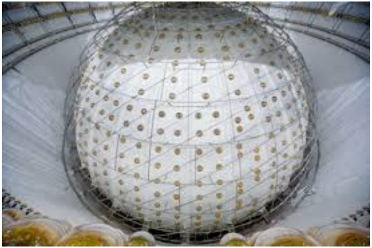


Figure 1: Artistic view of the CD.

# The Ultimate Goal: Parameter Reduction

**Why look for texture zeros? The main advantage:**

Every confirmed zero **reduces the number of free parameters**.

**HYPOTHESIS: TEXTURE ZERO PATTERN**

Can this specific matrix structure reproduce the real oscillation data?

$\swarrow$ **YES** $\qquad\qquad$ $\searrow$ **NO**

**Allowed Texture**

- **Parameter reduction:** Goal achieved.
- The model gains strong predictive power.
- Allows to mathematically calculate unknowns (e.g., the $\delta_{CP}$ phase).

**Rejected Texture**

- **Brutal elimination:** Conflict with experimental data.
- This mass matrix structure is definitively excluded.
- Narrows down the pool of potential theories.

# Neutrino Textures: Combinatorics & Matrix Types

**Symmetric & Hermitian**
(Majorana / Hermitian Dirac)

Constraints ($m_{ij} = m_{ji}$ or $m_{ij} = m_{ji}^*$) reduce the matrix to **6 independent positions**.

A texture zero at $(i, j)$ automatically forces a zero at $(j, i)$.

$$\binom{6}{k} = \frac{6!}{k!(6-k)!}$$

- $k = 1$: 6 possible textures
- $k = 2$: 15 possible textures
- $k \geq 3$ **Zeros:** Falsified by current oscillation data.

**General Non-Symmetric**
(General Dirac mass matrix)

Without symmetry constraints, all entries are fully independent, giving **9 independent positions**.

Zeros at $(i, j)$ and $(j, i)$ are completely decoupled.

$$\binom{9}{k} = \frac{9!}{k!(9-k)!}$$

- $k = 1$: 9 possible textures
- $k = 2$: 36 possible textures
- $k = 3$: 84 possible textures

# Two-Zero Textures: The Surviving Models

Out of the 15 historically possible two-zero textures, current neutrino oscillation data leaves only a select few viable classes.

**Viable for BOTH Hermitian Dirac and Majorana:**

**Texture $A_1$**

$$\begin{pmatrix} 0 & 0 & X \\ 0 & X & X \\ X & X & X \end{pmatrix}$$

**Texture $A_2$**

$$\begin{pmatrix} 0 & X & 0 \\ X & X & X \\ 0 & X & X \end{pmatrix}$$

**Texture $C$**

$$\begin{pmatrix} X & X & X \\ X & 0 & X \\ X & X & 0 \end{pmatrix}$$

---

**Viable ONLY for Majorana:**

**Texture $B_1$**

$$\begin{pmatrix} X & X & 0 \\ X & 0 & X \\ 0 & X & X \end{pmatrix}$$

**Texture $B_2$**

$$\begin{pmatrix} X & 0 & X \\ 0 & X & X \\ X & X & 0 \end{pmatrix}$$

**Texture $B_3$**

$$\begin{pmatrix} X & 0 & X \\ 0 & 0 & X \\ X & X & X \end{pmatrix}$$

**Texture $B_4$**

$$\begin{pmatrix} X & X & 0 \\ X & X & X \\ 0 & X & 0 \end{pmatrix}$$

# Two-Zero Majorana Textures: Experimental Verdict

## Majorana Textures (Classes A and C):

**Texture $A_1$**

$$\begin{pmatrix} 0 & 0 & X \\ 0 & X & X \\ X & X & X \end{pmatrix}$$

NUFIT 6.0: IH EXCLUDED

✓ VIABLE (NH)

~~**Texture $A_2$**~~

$$\cancel{\begin{pmatrix} 0 & X & 0 \\ X & X & X \\ 0 & X & X \end{pmatrix}}$$

NUFIT 6.0 EXCLUDED

X REJECTED

**Texture $C$**

$$\begin{pmatrix} X & X & X \\ X & 0 & X \\ X & X & 0 \end{pmatrix}$$

✓ VIABLE

---

## Majorana Textures (Class B):

**Texture $B_1$**

$$\begin{pmatrix} X & X & 0 \\ X & 0 & X \\ 0 & X & X \end{pmatrix}$$

JUNO: NH EXCLUDED

✓ VIABLE (IH)

**Texture $B_2$**

$$\begin{pmatrix} X & 0 & X \\ 0 & X & X \\ X & X & 0 \end{pmatrix}$$

✓ VIABLE

**Texture $B_3$**

$$\begin{pmatrix} X & 0 & X \\ 0 & 0 & X \\ X & X & X \end{pmatrix}$$

✓ VIABLE

**Texture $B_4$**

$$\begin{pmatrix} X & X & 0 \\ X & X & X \\ 0 & X & 0 \end{pmatrix}$$

✓ VIABLE

Data based on: D. Borah, P. Das, D. Dutta, arXiv:2512.13587 [hep-ph]

**Texture $A_1$**

$$\begin{pmatrix} 0 & 0 & X \\ 0 & X & X \\ X & X & X \end{pmatrix}$$

JUNO: IH EXCLUDED

✓ VIABLE (NH)

**Texture $A_2$**

$$\begin{pmatrix} 0 & X & 0 \\ X & X & X \\ 0 & X & X \end{pmatrix}$$

NUFIT 6.0: IH EXCLUDED

✓ VIABLE (NH)

**Texture $C$**

$$\begin{pmatrix} X & X & X \\ X & 0 & X \\ X & X & 0 \end{pmatrix}$$

JUNO: FULLY EXCLUDED

X REJECTED

Data based on: Priya, R. K. Kumar, L. Singh, S. Verma, arXiv:2604.19122 [hep-ph]

# One-Zero Textures: The 6 Possibilities

As two-zero textures become increasingly constrained by experimental data, one-zero textures offer a more relaxed phenomenological framework. For a Hermitian Dirac and Majorana mass matrix, there are exactly **6 possible patterns**:

**Texture** $G1$

$$\begin{pmatrix} 0 & X & X \\ X & X & X \\ X & X & X \end{pmatrix}$$

**Texture** $G2$

$$\begin{pmatrix} X & 0 & X \\ 0 & X & X \\ X & X & X \end{pmatrix}$$

**Texture** $G3$

$$\begin{pmatrix} X & X & 0 \\ X & X & X \\ 0 & X & X \end{pmatrix}$$

**Texture** $G4$

$$\begin{pmatrix} X & X & X \\ X & 0 & X \\ X & X & X \end{pmatrix}$$

**Texture** $G5$

$$\begin{pmatrix} X & X & X \\ X & X & 0 \\ X & 0 & X \end{pmatrix}$$

**Texture** $G6$

$$\begin{pmatrix} X & X & X \\ X & X & X \\ X & X & 0 \end{pmatrix}$$

*Note: Unlike two-zero models, all six one-zero Hermitian Dirac and Majorana mass textures are currently compatible with global neutrino oscillation fits.*

# One-Zero Majorana Textures: Oscillation Limits Only

**Texture** $G1$

$$\begin{pmatrix} 0 & X & X \\ X & X & X \\ X & X & X \end{pmatrix}$$

**NUFIT 6.0: IH EXCLUDED**

✓ VIABLE (NH)

**Texture** $G2$

$$\begin{pmatrix} X & 0 & X \\ 0 & X & X \\ X & X & X \end{pmatrix}$$

✓ FULLY VIABLE

**Texture** $G3$

$$\begin{pmatrix} X & X & 0 \\ X & X & X \\ 0 & X & X \end{pmatrix}$$

✓ FULLY VIABLE

**Texture** $G4$

$$\begin{pmatrix} X & X & X \\ X & 0 & X \\ X & X & X \end{pmatrix}$$

✓ FULLY VIABLE

**Texture** $G5$

$$\begin{pmatrix} X & X & X \\ X & X & 0 \\ X & 0 & X \end{pmatrix}$$

✓ FULLY VIABLE

**Texture** $G6$

$$\begin{pmatrix} X & X & X \\ X & X & X \\ X & X & 0 \end{pmatrix}$$

✓ FULLY VIABLE

Data based on: D. Borah, P. Das, D. Dutta, arXiv:2512.13587 [hep-ph]

# One-Zero Dirac Textures: Oscillation Data ($3\sigma$)

**Texture $G1$**

$$\begin{pmatrix} 0 & X & X \\ X & X & X \\ X & X & X \end{pmatrix}$$

OSC. DATA: IO EXCLUDED

✓ VIABLE (NO)

**Texture $G2$**

$$\begin{pmatrix} X & 0 & X \\ 0 & X & X \\ X & X & X \end{pmatrix}$$

OSC. DATA: IO EXCLUDED

✓ VIABLE (NO)

**Texture $G3$**

$$\begin{pmatrix} X & X & 0 \\ X & X & X \\ 0 & X & X \end{pmatrix}$$

OSC. DATA: IO EXCLUDED

✓ VIABLE (NO)

**Texture $G4$**

$$\begin{pmatrix} X & X & X \\ X & 0 & X \\ X & X & X \end{pmatrix}$$

✓ FULLY VIABLE

**Texture $G5$**

$$\begin{pmatrix} X & X & X \\ X & X & 0 \\ X & 0 & X \end{pmatrix}$$

OSC. DATA: NO EXCLUDED

✓ VIABLE (IO)

**Texture $G6$**

$$\begin{pmatrix} X & X & X \\ X & X & X \\ X & X & 0 \end{pmatrix}$$

✓ FULLY VIABLE

Data based on: R. H. Benavides, Y. Lenis, J. D. Gómez, W. A. Ponce, Chinese Physics C 50 (2026) 3, arXiv:2508.18611 [hep-ph]

# Future Directions

- We plan to explore additional research directions beyond what is presented here.
- Developing a Mathematica program to simplify complex equations. It then uses numerical methods to find the exact physical solutions.

Thank you for your attention!