Flavor-deconstructed neutrinos

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Based on work in collaboration with
Mario Fernández Navarro and **Stephen F. King**

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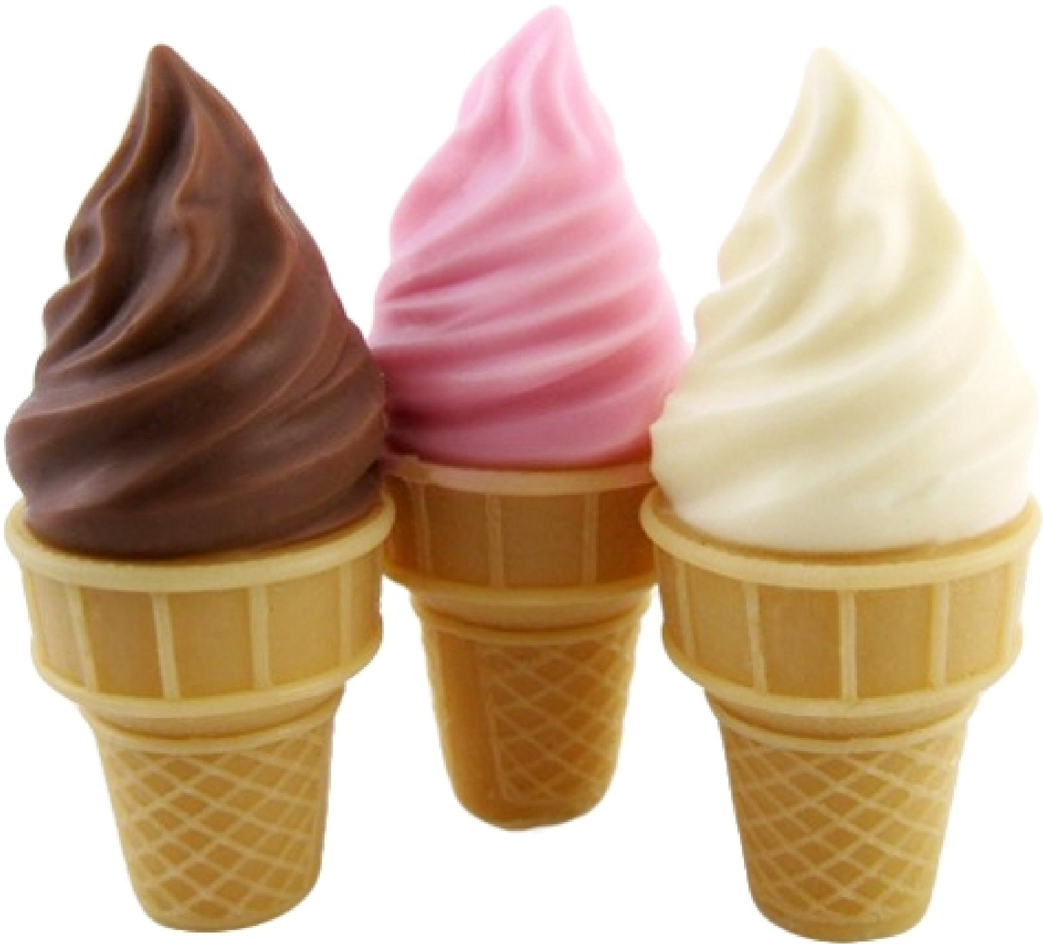
Rome

The flavor puzzle



Deconstructing flavor

General idea:

SM embedded in a larger gauge symmetry with a separate factor for each family

$$\boldsymbol{G = G_{\text{universal}} \times G_1 \times G_2 \times G_3}$$

The SM Higgs is a 3rd family particle: singlet of G_1 and G_2, but not of G_3

⇨ Only the 3rd family masses at renormalizable level

$$\mathcal{L} = y_t \, q_3 H u_3^c + y_b \, q_3 \widetilde{H} d_3^c + y_\tau \, \ell_3 \widetilde{H} e_3^c$$

⇨ Explain the SM flavor structure with $\mathcal{O}(1)$ Yukawa couplings via non-renormalizable operators (which can be UV- completed)

Deconstructing flavor

Examples:

- Tri-hypercharge: $SU(3)_c \times SU(2)_L \times U(1)_Y^3$ [Fernández Navarro, King, AV]

This talk

- $SU(3)_c \times SU(2)_L^3 \times U(1)_Y$ [Li, Ma, Muller, Nandi, Chiang, Deshpande, He, Jiang, Davighi...]
- $SU(3)_c^3 \times SU(2)_L \times U(1)_Y$ [Carone, Murayama]
- (Pati-Salam)^3 [Bordone, Cornella, Fuentes-Martin, Isidori, Pagès, Stefanek...]
- Grand unified models [Rajpoot, Barbieri, Dvali, Strumia, Babu, Barr, Gogoladze...]

+ other groups

+ other authors

(apologies if I missed your contribution!)

The lepton sector

Flavor-deconstructed models naturally explain hierarchies

They typically generate...

- Large quark and charged lepton mass hierarchies
- Small quark mixing : V_{CKM}
- <u>However</u>, also small lepton mixing : V_{PMNS}

Example: Tri-hypercharge

[Fernández Navarro, King, AV, 2024]

Field	$U(1)_{Y_1}$	$U(1)_{Y_2}$	$U(1)_{Y_3}$	$SU(3)_c \times SU(2)_L$
ℓ_1	$-\frac{1}{2}$	0	0	$(\mathbf{1}, \mathbf{2})$
ℓ_2	0	$-\frac{1}{2}$	0	$(\mathbf{1}, \mathbf{2})$
ℓ_3	0	0	$-\frac{1}{2}$	$(\mathbf{1}, \mathbf{2})$
ν_1^c	0	0	0	$(\mathbf{1}, \mathbf{1})$
ν_2^c	0	0	0	$(\mathbf{1}, \mathbf{1})$
H_u	0	0	$\frac{1}{2}$	$(\mathbf{1}, \mathbf{2})$
H_d	0	0	$-\frac{1}{2}$	$(\mathbf{1}, \mathbf{2})$
ϕ_{12}	$\frac{1}{2}$	$-\frac{1}{2}$	0	$(\mathbf{1}, \mathbf{1})$
ϕ_{23}	0	$\frac{1}{2}$	$-\frac{1}{2}$	$(\mathbf{1}, \mathbf{1})$

Minimal lepton sector

(quark sector in backup)

$$\boxed{SU(3)_c \times SU(2)_L \times U(1)_{Y_1} \times U(1)_{Y_2} \times U(1)_{Y_3}}$$

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→ **Lepton doublets**

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→ **Lepton doublets**

→ **Two right-handed neutrinos**
(complete gauge singlets)

Minimal lepton sector
(quark sector in backup)

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→ **Lepton doublets**

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→ **Higgs doublets** : 3rd family particles
(Type-II 2HDM to get up/down hierarchies)

Minimal lepton sector
(quark sector in backup)

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$\longrightarrow$ **Lepton doublets**

$\longrightarrow$ **Two right-handed neutrinos**
(complete gauge singlets)

$\longrightarrow$ **Higgs doublets** : 3rd family particles
(Type-II 2HDM to get up/down hierarchies)

$\longrightarrow$ **Hyperons**
Non-zezo individual hypercharges but vanishing total hypercharge

$$U(1)_{Y_1} \times U(1)_{Y_2} \times U(1)_{Y_3} \to U(1)_Y$$

$$Y_1 + Y_2 + Y_3 = Y$$

Minimal lepton sector
(quark sector in backup)

$$\boxed{SU(3)_c \times SU(2)_L \times U(1)_{Y_1} \times U(1)_{Y_2} \times U(1)_{Y_3}}$$

Example: Tri-hypercharge

$$\mathcal{L} = a^{\nu}_{3i} \ell_3 H_u \nu^c_i + a^{\nu}_{2i} \frac{\phi_{23}}{\Lambda^{\nu}_{23}} \ell_2 H_u \nu^c_i + a^{\nu}_{1i} \frac{\phi_{12}}{\Lambda^{\nu}_{12}} \frac{\phi_{23}}{\Lambda^{\nu}_{23}} \ell_1 H_u \nu^c_i + M_{ij} \nu^c_i \nu^c_j + \text{h.c.}$$

$$\begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \end{pmatrix} \underbrace{\overbrace{\begin{pmatrix} a^{\nu}_{11} \epsilon^{\nu}_{12} \epsilon^{\nu}_{23} & a^{\nu}_{12} \epsilon^{\nu}_{12} \epsilon^{\nu}_{23} \\ a^{\nu}_{21} \epsilon^{\nu}_{23} & a^{\nu}_{22} \epsilon^{\nu}_{23} \\ a^{\nu}_{31} & a^{\nu}_{32} \end{pmatrix}}^{\boldsymbol{m_D}}}_{\textbf{hierarchical}} \begin{pmatrix} \nu^c_1 \\ \nu^c_2 \end{pmatrix} H_u + \begin{pmatrix} \nu^c_1 & \nu^c_2 \end{pmatrix} \underbrace{\overbrace{\begin{pmatrix} M_{22} & M_{23} \\ M_{32} & M_{33} \end{pmatrix}}^{\boldsymbol{M_M}}}_{\textbf{anarchic}} \begin{pmatrix} \nu^c_1 \\ \nu^c_2 \end{pmatrix}$$

$$\begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \end{pmatrix} \overbrace{\begin{pmatrix} a^{e}_{11} \epsilon^{e}_{12} \epsilon^{e}_{23} & a^{e}_{12} \epsilon^{e}_{12} \epsilon^{e}_{23} & a^{e}_{13} \epsilon^{e}_{12} \epsilon^{e}_{23} \\ a^{e}_{21} (\epsilon^{e}_{12})^2 \epsilon^{e}_{23} & a^{e}_{22} \epsilon^{e}_{23} & a^{e}_{23} \epsilon^{e}_{23} \\ a^{e}_{31} (\epsilon^{e}_{12})^2 (\epsilon^{e}_{23})^2 & a^{e}_{32} (\epsilon^{e}_{23})^2 & a^{e}_{33} \end{pmatrix}}^{\boldsymbol{m_e}} \begin{pmatrix} e^c_1 \\ e^c_2 \\ e^c_3 \end{pmatrix} H_d$$

~ diagonal and hierarchical

Hierarchical lepton sector with small mixing angles

(unless the dimensionless order 1 coefficients are tuned)

$$\epsilon^a_{ij} = \frac{\langle \phi_{ij} \rangle}{\Lambda^a_{ij}} \ll 1$$

Ways out

- Introduce extra linking scalars (e.g. hyperons) which only participate in the neutrino sector and change the Yukawa texture

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- Consider particular gauge symmetries where both hierarchical m_D and hierarchical M_M cancel the overall hierarchies in the neutrino mass matrix

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- Consider particular gauge symmetries where both hierarchical m_D and hierarchical M_M cancel the overall hierarchies in the neutrino mass matrix

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- Charge all lepton doublets under the same site (e.g. hypercharge) and assume that the resulting gauge anomalies are cancelled with extra fermions in the UV

  [Fuentes-Martín, Lizana]

Ways out

However...

All these approaches lead to an *anarchic* effective neutrino mass matrix

All entries are governed by $O(1)$ coefficients which are fitted to neutrino oscillation data

- Introduce extra linking scalars (e.g. hyperons) which only participate in the neutrino sector and change the Yukawa texture

  [Fernández Navarro, King]

- Go beyond the validity of the EFT approach to generate $\epsilon \sim 1$ in the full UV theory

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- Consider particular gauge symmetries where both hierarchical m_D and hierarchical M_M cancel the overall hierarchies in the neutrino mass matrix

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- ... under the same site (e.g. hypercharge) and assume that the resulting gauge anomalies are cancelled with extra fermions in the UV

  [Fuentes-Martín, Lizana]

Our new proposal

Mario Fernández Navarro, Stephen F. King, AV

2506.21687

"From anarchy to order"

Key observation:

The two right-handed neutrinos are both singlets under the tri-hypercharge gauge group, and hence are indistinguishable, which results in the two columns of the Dirac matrix being approximately equal and the Majorana matrix being anarchical

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Extend tri-hypercharge to a larger gauge group under which the right-handed neutrinos are not singlets

$$G_{\mathrm{TH}} = U(1)_{Y_1} \times U(1)_{Y_2} \times U(1)_{Y_3}$$

$$\downarrow$$

$$G_{\mathrm{UV}} = U(1)_{Y_1} \times U(1)_{R_2} \times U(1)_{(B-L)_2/2} \times U(1)_{R_3} \times U(1)_{(B-L)_3/2}$$

$$Y_i = R_i + \frac{1}{2}(B-L)_i$$
$$i = 2, 3$$

Field	$U(1)_{Y_1}$	$U(1)_{R_2} \times U(1)_{(B-L)_2/2}$	$U(1)_{R_3} \times U(1)_{(B-L)_3/2}$	$SU(3)_c \times SU(2)_L$
ℓ_1	$-\frac{1}{2}$	$(0,0)$	$(0,0)$	$(\mathbf{1},\mathbf{2})$
ℓ_2	0	$(0,-\frac{1}{2})$	$(0,0)$	$(\mathbf{1},\mathbf{2})$
ℓ_3	0	$(0,0)$	$(0,-\frac{1}{2})$	$(\mathbf{1},\mathbf{2})$
e_1^c	1	$(0,0)$	$(0,0)$	$(\mathbf{1},\mathbf{1})$
e_2^c	0	$(\frac{1}{2},\frac{1}{2})$	$(0,0)$	$(\mathbf{1},\mathbf{1})$
e_3^c	0	$(0,0)$	$(\frac{1}{2},\frac{1}{2})$	$(\mathbf{1},\mathbf{1})$
ν_2^c	0	$(-\frac{1}{2},\frac{1}{2})$	$(0,0)$	$(\mathbf{1},\mathbf{1})$
ν_3^c	0	$(0,0)$	$(-\frac{1}{2},\frac{1}{2})$	$(\mathbf{1},\mathbf{1})$
$H_{u,d}$	0	$(0,0)$	$(\pm\frac{1}{2},0)$	$(\mathbf{1},\mathbf{2})$
χ_2	0	$(1,-1)$	$(0,0)$	$(\mathbf{1},\mathbf{1})$
χ_3	0	$(0,0)$	$(1,-1)$	$(\mathbf{1},\mathbf{1})$
ϕ_{12}^R	$\frac{1}{2}$	$(-\frac{1}{2},0)$	$(-\frac{1}{2},0)$	$(\mathbf{1},\mathbf{1})$
ϕ_{12}^L	$\frac{1}{2}$	$(0,-\frac{1}{2})$	$(0,0)$	$(\mathbf{1},\mathbf{1})$
ϕ_{23}^R	0	$(\frac{1}{2},0)$	$(-\frac{1}{2},0)$	$(\mathbf{1},\mathbf{1})$
ϕ_{23}^L	0	$(0,\frac{1}{2})$	$(0,-\frac{1}{2})$	$(\mathbf{1},\mathbf{1})$

$$\boxed{G_{\rm UV} \xrightarrow{\langle \chi_i \rangle} G_{\rm TH} \xrightarrow{\langle \phi_{ij} \rangle} {\rm SM}}$$

The lepton sector

$$\begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \end{pmatrix} \overbrace{\begin{pmatrix} a^\nu_{12}\epsilon^L_{12}\epsilon^R_{23} & a^\nu_{13}\epsilon^L_{12}\epsilon^L_{23} \\ a^\nu_{22}\epsilon^R_{23} & a^\nu_{23}\epsilon^L_{23} \\ a^\nu_{32}\epsilon^L_{23}\epsilon^R_{23} & a^\nu_{33} \end{pmatrix}}^{\boldsymbol{m_D}} \begin{pmatrix} \nu^c_1 \\ \nu^c_2 \end{pmatrix} H_u + \begin{pmatrix} \nu^c_1 & \nu^c_2 \end{pmatrix} \overbrace{\begin{pmatrix} \chi_2 & \epsilon^L_{23}\epsilon^R_{23}\chi_3 \\ \epsilon^L_{23}\epsilon^R_{23}\chi_3 & \chi_3 \end{pmatrix}}^{\boldsymbol{M_M}} \begin{pmatrix} \nu^c_1 \\ \nu^c_2 \end{pmatrix}$$

~ diagonal

hierarchical by columns

$$\begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \end{pmatrix} \overbrace{\begin{pmatrix} a^e_{11}\epsilon^R_{12}\epsilon^R_{23} & a^e_{12}\epsilon^L_{12}\epsilon^R_{23} & a^e_{13}\epsilon^L_{12}\epsilon^L_{23} \\ a^e_{21}\epsilon^L_{12}\epsilon^R_{12}\epsilon^R_{23} & a^e_{22}\epsilon^R_{23} & a^e_{23}\epsilon^L_{23} \\ a^e_{31}\epsilon^L_{12}\epsilon^R_{12}\epsilon^L_{23}\epsilon^R_{23} & a^e_{32}\epsilon^L_{23}\epsilon^R_{23} & a^e_{33} \end{pmatrix}}^{\boldsymbol{m_e}} \begin{pmatrix} e^c_1 \\ e^c_2 \\ e^c_3 \end{pmatrix} H_d$$

~ diagonal and hierarchical

The lepton sector

$$\begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \end{pmatrix} \overbrace{\begin{pmatrix} a^\nu_{12}\epsilon^L_{12}\epsilon^R_{23} & a^\nu_{13}\epsilon^L_{12}\epsilon^L_{23} \\ a^\nu_{22}\epsilon^R_{23} & a^\nu_{23}\epsilon^L_{23} \\ a^\nu_{32}\epsilon^L_{23}\epsilon^R_{23} & a^\nu_{33} \end{pmatrix}}^{\boldsymbol{m_D}} \begin{pmatrix} \nu^c_1 \\ \nu^c_2 \end{pmatrix} H_u + \begin{pmatrix} \nu^c_1 & \nu^c_2 \end{pmatrix} \overbrace{\begin{pmatrix} \chi_2 & \epsilon^L_{23}\epsilon^R_{23}\chi_3 \\ \epsilon^L_{23}\epsilon^R_{23}\chi_3 & \chi_3 \end{pmatrix}}^{\boldsymbol{M_M}} \begin{pmatrix} \nu^c_1 \\ \nu^c_2 \end{pmatrix}$$

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~ diagonal and hierarchical

$$m_e \sim \epsilon^R_{12}\epsilon^R_{23}\langle H_d\rangle$$

$$m_\mu \sim \epsilon^R_{23}\langle H_d\rangle \quad \Longrightarrow$$

$$m_\tau \sim \langle H_d\rangle$$

$$\epsilon^R_{12} \sim \frac{m_e}{m_\mu} \simeq 0.005$$

$$\epsilon^R_{23} \sim \frac{m_\mu}{m_\tau} \simeq 0.06$$

The lepton sector

$$\boldsymbol{m_D} \qquad\qquad \boldsymbol{M_M}$$

$$\begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \end{pmatrix} \begin{pmatrix} a^\nu_{12}\epsilon^L_{12}\epsilon^R_{23} & a^\nu_{13}\epsilon^L_{12}\epsilon^L_{23} \\ a^\nu_{22}\epsilon^R_{23} & a^\nu_{23}\epsilon^L_{23} \\ a^\nu_{32}\epsilon^L_{23}\epsilon^R_{23} & a^\nu_{33} \end{pmatrix} \begin{pmatrix} \nu^c_1 \\ \nu^c_2 \end{pmatrix} H_u + \begin{pmatrix} \nu^c_1 & \nu^c_2 \end{pmatrix} \begin{pmatrix} \chi_2 & \epsilon^L_{23}\epsilon^R_{23}\chi_3 \\ \epsilon^L_{23}\epsilon^R_{23}\chi_3 & \chi_3 \end{pmatrix} \begin{pmatrix} \nu^c_1 \\ \nu^c_2 \end{pmatrix}$$

~ diagonal

hierarchical by columns

$$\boldsymbol{m_e}$$

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$$m_e \sim \epsilon^R_{12}\epsilon^R_{23}\langle H_d\rangle$$

$$m_\mu \sim \epsilon^R_{23}\langle H_d\rangle$$

$$m_\tau \sim \langle H_d\rangle$$

$$\Longrightarrow$$

$$\epsilon^R_{12} \sim \frac{m_e}{m_\mu} \simeq 0.005$$

$$\epsilon^R_{23} \sim \frac{m_\mu}{m_\tau} \simeq 0.06$$

$$+$$

$$\epsilon^L_{12,23} \gtrsim 0.1$$

$$\langle\chi_2\rangle \sim 10^{13}\ \text{GeV}$$

$$\langle\chi_3\rangle \sim 10^{14}\ \text{GeV}$$

$$\mathcal{O}(1)\ a\text{'s}$$

Neutrino data reproduced 😁

The lepton sector

$$\boldsymbol{m_D}$$

$$\begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \end{pmatrix} \begin{pmatrix} a^\nu_{12}\epsilon^L_{12}\epsilon^R_{23} & a^\nu_{13}\epsilon^L_{12}\epsilon^L_{23} \\ a^\nu_{22}\epsilon^R_{23} & a^\nu_{23}\epsilon^L_{23} \\ a^\nu_{32}\epsilon^L_{23}\epsilon^R_{23} & a^\nu_{33} \end{pmatrix} \begin{pmatrix} \nu^c_1 \\ \nu^c_2 \end{pmatrix} H_u + \begin{pmatrix} \nu^c_1 & \nu^c_2 \end{pmatrix} \begin{pmatrix} \chi_2 & \epsilon^L_{23}\epsilon^R_{23}\chi_3 \\ \epsilon^L_{23}\epsilon^R_{23}\chi_3 & \chi_3 \end{pmatrix} \begin{pmatrix} \nu^c_1 \\ \nu^c_2 \end{pmatrix}$$

$$\boldsymbol{M_M}$$

~ diagonal

hierarchical by columns

$$\boldsymbol{m_e}$$

$$\begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \end{pmatrix} \begin{pmatrix} a^e_{11}\epsilon^R_{12}\epsilon^R_{23} & a^e_{12}\epsilon^L_{12}\epsilon^R_{23} & a^e_{13}\epsilon^L_{12}\epsilon^L_{23} \\ a^e_{21}\epsilon^L_{12}\epsilon^R_{12}\epsilon^R_{23} & a^e_{22}\epsilon^R_{23} & a^e_{23}\epsilon^L_{23} \\ a^e_{31}\epsilon^L_{12}\epsilon^R_{12}\epsilon^L_{23}\epsilon^R_{23} & a^e_{32}\epsilon^L_{23}\epsilon^R_{23} & a^e_{33} \end{pmatrix} \begin{pmatrix} e^c_1 \\ e^c_2 \\ e^c_3 \end{pmatrix} H_d$$

~ diagonal and hierarchical

Enforced by the hierarchical column structure of the Yukawa textures in the charged lepton and neutrino sectors

$$\boxed{\textbf{Sequential dominance}}$$

From anarchy... to order!

Neutrino data reproduced 😁

Sequential dominance

A sub-mechanism within the type-I seesaw [King, Antusch]

In the neutrino sector:

SD condition

$$m_D = \begin{pmatrix} a' & a & d \\ b' & b & e \\ c' & c & f \end{pmatrix} \qquad M_{\rm M} = \begin{pmatrix} X' & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & Y \end{pmatrix} \qquad \frac{|e|^2, |f|^2, |e\, f|}{Y} \gg \frac{|x\, y|}{X} \gg \frac{|x' y'|}{X'}$$

ν_3^c contributes dominantly and determines the atmospheric neutrino mass and mixing

ν_2^c contributes subdominantly and determines the solar neutrino mass and mixing

ν_1^c is effectively decoupled

In the charged lepton sector:

SD condition

$$m_e = \begin{pmatrix} a' & a & d \\ b' & b & e \\ c' & c & f \end{pmatrix} \qquad |d|\,, |e|\,, |f| \gg |a|\,, |b|\,, |c| \gg |a'|\,, |b'|\,, |c'|$$

Simple formulas can be obtained in the form of a series expansion

Consequences

- Normal neutrino mass ordering: $m_3^2 \gg m_2^2 \gg m_1^2$

- $m_1 = 0$

- Naturally hierarchical charged leptons and suppressed right-handed charged lepton mixing

- Both sectors contribute to $U_{\text{PMNS}} = U_e U_\nu^\dagger$

  θ_{23} from both sectors, with a mild tuning

  $\theta_{13} \sim \sin\theta_{12}^e \sim \epsilon_{12}^L \sim 0.1$

  $\theta_{12} \approx \theta_{12}^\nu$

- Simple analytical formulas at leading order in the SD expansion

Final remarks

Take-home messages

Flavor deconstruction is a successful way to generate the flavor structure of the SM and tri-hypercharge is a simple way to implement it

The lepton sector is a challenge in flavor-deconstructed models, which have traditionally resorted to anarchy

Decomposing tri-hypercharge as $\boldsymbol{U(1)_{Y_i} \to U(1)_{R_i} \times U(1)_{(B-L)_i/2}}$ naturally leads to sequential dominance: order in the lepton sector!

- ☆ Predictions: normal neutrino mass ordering + a massless neutrino
- ☆ Both sectors contribute to lepton mixing
- ☆ Simple analytical formulas

Take-home messages

Flavor deconstruction is a successful way to generate the flavor structure of the SM and tri-hypercharge is a simple way to implement it

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Decomposing tri-hypercharge as $U(1)_{Y_i} \to U(1)_{R_i} \times U(1)_{(B-L)_i/2}$ naturally leads to sequential dominance: order in the lepton sector!

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Thank you!

Backup slides

The quark sector

Field	$U(1)_{Y_1}$	$U(1)_{R_2} \times U(1)_{(B-L)_2/2}$	$U(1)_{R_3} \times U(1)_{(B-L)_3/2}$	$SU(3)_c \times SU(2)_L$
q_1	$\frac{1}{6}$	$(0,0)$	$(0,0)$	$(\mathbf{3},\mathbf{2})$
q_2	0	$(0,\frac{1}{6})$	$(0,0)$	$(\mathbf{3},\mathbf{2})$
q_3	0	$(0,0)$	$(0,\frac{1}{6})$	$(\mathbf{3},\mathbf{2})$
u_1^c	$-\frac{2}{3}$	$(0,0)$	$(0,0)$	$(\overline{\mathbf{3}},\mathbf{1})$
u_2^c	0	$(-\frac{1}{2},-\frac{1}{6})$	$(0,0)$	$(\overline{\mathbf{3}},\mathbf{1})$
u_3^c	0	$(0,0)$	$(-\frac{1}{2},-\frac{1}{6})$	$(\overline{\mathbf{3}},\mathbf{1})$
d_1^c	$\frac{1}{3}$	$(0,0)$	$(0,0)$	$(\overline{\mathbf{3}},\mathbf{1})$
d_2^c	0	$(\frac{1}{2},-\frac{1}{6})$	$(0,0)$	$(\overline{\mathbf{3}},\mathbf{1})$
d_3^c	0	$(0,0)$	$(\frac{1}{2},-\frac{1}{6})$	$(\overline{\mathbf{3}},\mathbf{1})$
ϕ_{12}^q	$-\frac{1}{6}$	$(0,\frac{1}{6})$	$(0,0)$	$(\mathbf{1},\mathbf{1})$
ϕ_{23}^q	0	$(0,-\frac{1}{6})$	$(0,\frac{1}{6})$	$(\mathbf{1},\mathbf{1})$

The quark sector

$$\begin{pmatrix} q_1 & q_2 & q_3 \end{pmatrix} \begin{pmatrix} a^u_{11}\,\epsilon^R_{12}\epsilon^R_{23} & a^u_{12}\epsilon^q_{12}\epsilon^R_{23} & a^u_{13}\epsilon^q_{12}\epsilon^q_{23} \\ a^u_{21}\,\epsilon^q_{12}\epsilon^R_{12}\epsilon^R_{23} & a^u_{22}\epsilon^R_{23} & a^u_{23}\epsilon^q_{23} \\ a^u_{31}\,\epsilon^q_{12}\epsilon^R_{12}\epsilon^q_{23}\epsilon^R_{23} & a^u_{32}\epsilon^q_{23}\epsilon^R_{23} & a^u_{33} \end{pmatrix} \begin{pmatrix} u^c_1 \\ u^c_2 \\ u^c_3 \end{pmatrix} H_u$$

$$\begin{pmatrix} q_1 & q_2 & q_3 \end{pmatrix} \begin{pmatrix} a^d_{11}\,\epsilon^R_{12}\epsilon^R_{23} & a^d_{12}\epsilon^q_{12}\epsilon^R_{23} & a^d_{13}\epsilon^q_{12}\epsilon^q_{23} \\ a^d_{21}\,\epsilon^q_{12}\epsilon^R_{12}\epsilon^R_{23} & a^d_{22}\epsilon^R_{23} & a^d_{23}\epsilon^q_{23} \\ a^d_{31}\,\epsilon^q_{12}\epsilon^R_{12}\epsilon^q_{23}\epsilon^R_{23} & a^d_{32}\epsilon^q_{23}\epsilon^R_{23} & a^d_{33} \end{pmatrix} \begin{pmatrix} d^c_1 \\ d^c_2 \\ d^c_3 \end{pmatrix} H_d$$

$$m_u \sim \epsilon^R_{12}\epsilon^R_{23}\langle H_u\rangle \qquad m_d \sim \epsilon^R_{12}\epsilon^R_{23}\langle H_d\rangle$$

$$m_c \sim \epsilon^R_{23}\langle H_u\rangle \qquad m_s \sim \epsilon^R_{23}\langle H_d\rangle$$

$$m_t \sim \langle H_u\rangle \qquad m_b \sim \langle H_d\rangle$$

$$\epsilon^q_{23} \sim V_{cb} \sim 0.04$$

$$\epsilon^q_{12} \sim V_{us} \sim 0.2$$

Naturally hierarchical quarks and small quark mixing

Analytical formulas (I)

Neutrinos

Mixing angles:

$$\tan\theta_{23}^{\nu} \simeq \frac{|e|}{|f|} \qquad \theta_{13}^{\nu} \simeq \frac{|d|}{\sqrt{|e|^2+|f|^2}}$$

$$\tan\theta_{12}^{\nu} \simeq \frac{|a|}{c_{23}^{\nu}|b|\cos\tilde{\phi}_b^{\nu} - s_{23}^{\nu}|c|\cos\tilde{\phi}_c^{\nu}}$$

Masses:

$$m_3 \simeq \frac{|e|^2+|f|^2}{Y}$$

$$m_2 \simeq \frac{|a|^2}{X(s_{12}^{\nu})^2}$$

$$m_1 \simeq 0$$

Analytical formulas (II)

Charged leptons

Mixing angles:

$$\tan\theta_{23}^e \simeq \frac{|e|}{|f|} \qquad \theta_{13}^e \simeq \frac{|d|}{\sqrt{|e|^2+|f|^2}}$$

$$\tan\theta_{12}^e \simeq \frac{|a|}{c_{23}^e|b|\cos(\tilde{\phi}_b^e) - s_{23}^e|c|\cos(\tilde{\phi}_c^e)}$$

Masses:

$$m_\tau \simeq \sqrt{|e|^2+|f|^2}$$

$$m_\mu \simeq \frac{|a|}{s_{12}^e}$$

$$m_e \simeq |a'|c_{12}^e\cos(\tilde{\phi}_{a'}^e) - |b'|s_{12}^e c_{23}^e\cos(\tilde{\phi}_{b'}^e) + |c'|s_{12}^e s_{23}^e\cos(\tilde{\phi}_{c'}^e)$$