# Two viable models of SM fermion mass generation

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Planck 2017 Conference, Warsaw, Poland, 25th May of 2017.
Based on: A. E. Cárcamo Hernández, arxiv:hep-ph/1512.09092,
Eur.Phys.J. C76 (2016) no.9, 503.
A. E. Cárcamo Hernández, S. Kovalenko, I. Schmidt,
arxiv:hep-ph/1611.09797, JHEP 1702 (2017) 125.

The origin of fermion masses and mixings is not explained by the SM.

**FERMIONS** matter constituents
spin = 1/2, 3/2, 5/2, ...

**Leptons** spin =1/2

| Flavor | Mass GeV/c² | Electric charge |
|---|---|---|
| $\nu_L$ lightest neutrino* | (0−0.13)×10⁻⁹ | 0 |
| e electron | 0.000511 | −1 |
| $\nu_M$ middle neutrino* | (0.009−0.13)×10⁻⁹ | 0 |
| $\mu$ muon | 0.106 | −1 |
| $\nu_H$ heaviest neutrino* | (0.04−0.14)×10⁻⁹ | 0 |
| $\tau$ tau | 1.777 | −1 |

**Quarks** spin =1/2

| Flavor | Approx. Mass GeV/c² | Electric charge |
|---|---|---|
| u up | 0.002 | 2/3 |
| d down | 0.005 | −1/3 |
| c charm | 1.3 | 2/3 |
| s strange | 0.1 | −1/3 |
| t top | 173 | 2/3 |
| b bottom | 4.2 | −1/3 |

$$\sqrt{\left|\Delta m_{13}^2\right|} \sim \lambda^{20} m_t, \quad \sqrt{\Delta m_{12}^2} \sim \lambda^{21} m_t,$$

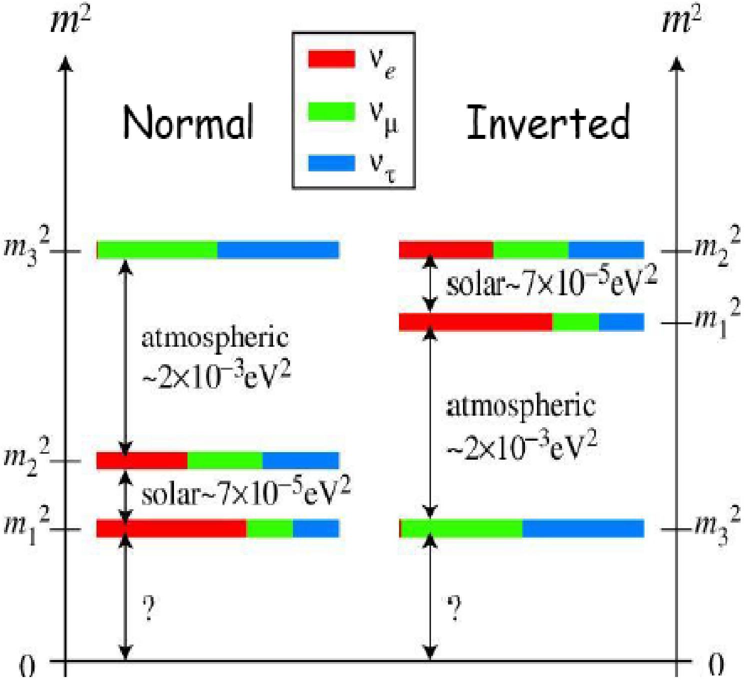
$$m_e \sim \lambda^9 m_t, \quad m_u \sim m_d \sim \lambda^8 m_t,$$

$$m_s \sim m_\mu \sim \lambda^5 m_t, \quad \lambda = 0.225,$$

$$m_c \sim \lambda^4 m_t, \quad m_b \sim m_\tau \sim \lambda^3 m_t,$$

$$\sin\theta_{12}^{(q)} \sim \lambda, \quad \sin\theta_{23}^{(q)} \sim \lambda^2, \quad \sin\theta_{13}^{(q)} \sim \lambda^4,$$

$$\sin\theta_{12}^{(l)} \sim \sqrt{\frac{1}{3}}, \quad \sin\theta_{23}^{(l)} \sim \sqrt{\frac{1}{2}}, \quad \sin\theta_{13}^{(l)} \sim \frac{\lambda}{\sqrt{2}}.$$


$m^2$
Normal
$\nu_e$
$\nu_\mu$
$\nu_\tau$
Inverted
$m^2$
$m_3{}^2$
atmospheric
$\sim 2\times10^{-3}$eV$^2$
$m_2{}^2$
solar$\sim 7\times10^{-5}$eV$^2$
$m_1{}^2$
?
0
$m_2{}^2$
solar$\sim 7\times10^{-5}$eV$^2$
$m_1{}^2$
atmospheric
$\sim 2\times10^{-3}$eV$^2$
$m_3{}^2$
?
0

The $S_3$ group has three irreducible representations: $\mathbf{1}$, $\mathbf{1}'$ and $\mathbf{2}$. Denoting the basis vectors for two $S_3$ doublets as $(x_1, x_2)^T$ and $(y_1, y_2)^T$ and $y'$ a non trivial $S_3$ singlet, the $S_3$ multiplication rules are (Ishimori, et al, Prog. Theor. Phys. Suppl 2010):

$$\begin{aligned}\left(\begin{array}{c} x_1 \\ x_2 \end{array}\right)_{\mathbf{2}} \otimes \left(\begin{array}{c} y_1 \\ y_2 \end{array}\right)_{\mathbf{2}} &= (x_1 y_1 + x_2 y_2)_{\mathbf{1}} + (x_1 y_2 - x_2 y_1)_{\mathbf{1}'} \\ &+ \left(\begin{array}{c} x_2 y_2 - x_1 y_1 \\ x_1 y_2 + x_2 y_1 \end{array}\right)_{\mathbf{2}}, \end{aligned} \tag{1}$$

$$\left(\begin{array}{c} x_1 \\ x_2 \end{array}\right)_{\mathbf{2}} \otimes (y')_{\mathbf{1}'} = \left(\begin{array}{c} -x_2 y' \\ x_1 y' \end{array}\right)_{\mathbf{2}}, \qquad (x')_{\mathbf{1}'} \otimes (y')_{\mathbf{1}'} = (x' y')_{\mathbf{1}}. \tag{2}$$

The $S_3$ symmetry is assumed to be softly broken whereas the $Z_8$ discrete group is broken at the scale $v_\chi$.

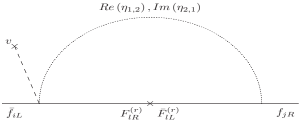
$$\phi \sim (\mathbf{1},1)\,, \qquad \eta = (\eta_1,\eta_2) \sim \left(\mathbf{2}, e^{-\frac{\pi i}{4}}\right), \qquad \chi \sim (\mathbf{1},-i)\,, \tag{3}$$

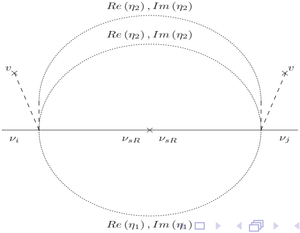
$$\begin{aligned}
q_{jL} &\sim \left(\mathbf{1}, e^{-\frac{\pi i(3-j)}{2}}\right), \quad u_{kR} \sim \left(\mathbf{1}', e^{\frac{\pi i(3-k)}{2}}\right), \quad u_{3R} \sim (\mathbf{1},1)\,, \\
d_{jR} &\sim \left(\mathbf{1}', e^{\frac{\pi i(3-j)}{2}}\right), \quad l_{jL} \sim \left(\mathbf{1}, e^{-\frac{\pi i(3-j)}{2}}\right), \quad l_{jR} \sim \left(\mathbf{1}', e^{\frac{\pi i(3-j)}{2}}\right), \\
T_L^{(k)} &\sim \left(\mathbf{2}, e^{-\frac{\pi i}{4}}\right), \qquad T_R^{(k)} \sim \left(\mathbf{2}, e^{\frac{\pi i}{4}}\right), \qquad k=1,2, \\
B_L^{(j)} &\sim \left(\mathbf{2}, e^{-\frac{\pi i}{4}}\right), \qquad B_R^{(j)} \sim \left(\mathbf{2}, e^{\frac{\pi i}{4}}\right), \qquad j=1,2,3, \\
E_L^{(j)} &\sim \left(\mathbf{2}, e^{-\frac{\pi i}{4}}\right), \qquad E_R^{(j)} \sim \left(\mathbf{2}, e^{\frac{\pi i}{4}}\right), \\
\nu_{kR} &\sim \left(\mathbf{1}', e^{-\frac{\pi i}{4}}\right), \qquad k=1,2.
\end{aligned} \tag{4}$$

We use the $S_3$ discrete group since it is the smallest non-Abelian group, having a doublet and two singlets as irreducible representations.

$$
\begin{aligned}
-\mathcal{L}_{\mathrm{Y}}^{(U)} &= \sum_{j=1}^{3}\sum_{r=1}^{2} y_{jr}^{(u)} \overline{q}_{jL}\widetilde{\phi}\left(T_R^{(r)}\eta\right)_{\mathbf{1}} \frac{\chi^{3-j}}{\Lambda^{4-j}} \\
&+ \sum_{r=1}^{2}\sum_{s=1}^{2} x_{rs}^{(u)} \left(\overline{T}_L^{(r)}\eta\right)_{\mathbf{1}'} u_{sR}\frac{\chi^{3-k}}{\Lambda^{3-k}} \\
&+ \sum_{j=1}^{3} y_{j3}^{(u)} \overline{q}_{jL}\widetilde{\phi} u_{3R}\frac{\chi^{3-j}}{\Lambda^{3-j}} + \sum_{r=1}^{2} y_r^{(T)} \left(\overline{T}_L^{(r)} T_R^{(r)}\right)_{\mathbf{1}} \chi + h.c
\end{aligned}
$$

$$
-\mathcal{L}_{\mathrm{Y}}^{(\nu)} = \sum_{j=1}^{3}\sum_{s=1}^{2} y_{js}^{(\nu)} \bar{l}_{jL}\widetilde{\phi}\nu_{sR}\frac{\left[\eta^{*}\left(\eta\eta^{*}\right)_{\mathbf{2}}\right]_{\mathbf{1}'}\chi^{3-j}}{\Lambda^{6-j}} + \sum_{s=1}^{2} y_s \overline{\nu}_{sR}\nu_{sR}^{C}\chi + h.c.
$$



$$
\begin{aligned}
-\mathcal{L}_{Y}^{(D)} &= \sum_{j=1}^{3}\sum_{k=1}^{3} y_{jk}^{(d)}\overline{q}_{jL}\phi\left(B_{R}^{(k)}\eta\right)_{\mathbf{1}}\frac{\chi^{3-j}}{\Lambda^{4-j}} \\
&+ \sum_{j=1}^{3}\sum_{k=1}^{3} x_{jk}^{(d)}\left(\overline{B}_{L}^{(j)}\eta\right)_{\mathbf{1}'} d_{kR}\frac{\chi^{3-k}}{\Lambda^{3-k}} \\
&+ \sum_{k=1}^{3} y_{k}^{(B)}\left(\overline{B}_{L}^{(k)}B_{R}^{(k)}\right)_{\mathbf{1}}\chi + h.c. \qquad (5)
\end{aligned}
$$

$$
\begin{aligned}
-\mathcal{L}_{Y}^{(l)} &= \sum_{j=1}^{3}\sum_{k=1}^{3} y_{jk}^{(l)}\overline{l}_{jL}\phi\left(E_{R}^{(k)}\eta\right)_{\mathbf{1}}\frac{\chi^{3-j}}{\Lambda^{4-j}} \\
&+ \sum_{j=1}^{3}\sum_{k=1}^{3} x_{jk}^{(l)}\left(\overline{E}_{L}^{(j)}\eta\right)_{\mathbf{1}'} l_{kR}\frac{\chi^{3-k}}{\Lambda^{3-k}} \\
&+ \sum_{k=1}^{3} y_{k}^{(E)}\left(\overline{E}_{L}^{(k)}E_{R}^{(k)}\right)_{\mathbf{1}}\chi \qquad (6)
\end{aligned}
$$

where I set

$$
v_{\chi} = \lambda\Lambda, \qquad \lambda = 0.225. \qquad (7)
$$

# Fermion masses and mixing.

The charged fermion mass matrices are:

$$M_U = \begin{pmatrix} \varepsilon_{11}^{(u)}\lambda^3 & \varepsilon_{12}^{(u)}\lambda^2 & y_{13}^{(u)}\lambda^2 \\ \varepsilon_{21}^{(u)}\lambda^2 & \varepsilon_{22}^{(u)}\lambda & y_{23}^{(u)}\lambda \\ \varepsilon_{31}^{(u)}\lambda & \varepsilon_{32}^{(u)} & y_{33}^{(u)} \end{pmatrix} \frac{v}{\sqrt{2}}, \qquad (8)$$

$$M_{D,l} = \begin{pmatrix} \varepsilon_{11}^{(d,l)}\lambda^4 & \varepsilon_{12}^{(d,l)}\lambda^3 & \varepsilon_{13}^{(d,l)}\lambda^2 \\ \varepsilon_{21}^{(d,l)}\lambda^3 & \varepsilon_{22}^{(d,l)}\lambda^2 & \varepsilon_{23}^{(d,l)}\lambda \\ \varepsilon_{31}^{(d,l)}\lambda^2 & \varepsilon_{32}^{(d,l)}\lambda & \varepsilon_{33}^{(d,l)} \end{pmatrix} \frac{v}{\sqrt{2}},$$

where the dimensionless parameters $\varepsilon_{jk}^{(f)}$ $(j,k = 1,2,3)$ with $f = u,d,l$, are generated at one loop level. The invariance of charged exotic fermion Yukawa interactions under the cyclic symmetry requires to consider the $Z_8$ instead of the $Z_4$ discrete symmetry.

The light active neutrino mass matrix is:

$$M_\nu = \begin{pmatrix} W_1^2 & W_1 W_2 \cos\varphi & W_1 W_3 \cos(\varphi - \varrho) \\ W_1 W_2 \cos\varphi & W_2^2 & W_2 W_3 \cos\varrho \\ W_1 W_3 \cos(\varphi - \varrho) & W_2 W_3 \cos\varrho & W_3^2 \end{pmatrix},$$

$$\overrightarrow{W}_j = \left( \frac{A_{j1}\sqrt{y_1 v_\chi f_1^{(\nu)}}}{64\pi^3\Lambda}, \frac{A_{j2}\sqrt{y_2 v_\chi f_2^{(\nu)}}}{64\pi^3\Lambda} \right), A_{js} = \lambda^{3-j} y_{js}^{(\nu)} \frac{v}{\sqrt{2}}$$

$$\cos\varphi = \frac{\overrightarrow{W}_1 \cdot \overrightarrow{W}_2}{\left|\overrightarrow{W}_1\right| \left|\overrightarrow{W}_2\right|}, \quad \cos(\varphi - \varrho) = \frac{\overrightarrow{W}_1 \cdot \overrightarrow{W}_3}{\left|\overrightarrow{W}_1\right| \left|\overrightarrow{W}_3\right|}, \quad \cos\varrho = \frac{\overrightarrow{W}_2 \cdot \overrightarrow{W}_3}{\left|\overrightarrow{W}_2\right| \left|\overrightarrow{W}_3\right|}$$

where the dimensionless parameters $f_s^{(\nu)}$ $(s = 1, 2)$ are generated at three loop level.

# A $S_3 \times Z_2$ flavor model

The fermion mass hierarchy is explained by a sequential loop suppression, so that the masses are generated according to:

$$t\text{-quark} \quad \rightarrow \quad \textit{tree-level mass} \text{ from} \quad \overline{q}_{jL}\widetilde{\phi}u_{3R}, \tag{9}$$

$$b, c, \ \tau, \mu \quad \rightarrow \quad \textit{1-loop mass;} \text{ tree-level suppressed by a } \textit{symmetry}. \tag{10}$$

$$s, u, d, \ e \quad \rightarrow \quad \textit{2-loop mass;} \text{ tree-level \& 1-loop suppressed by a } \textit{symmetry}. \tag{11}$$

$$\nu_i \quad \rightarrow \quad \textit{4-loop mass;} \text{ tree-level \& lower loops suppressed by a } \textit{symmetry}. \tag{12}$$

The mass matrices $M_{U,D}$ of up and down quarks, $M_{l,\nu}$, of charged leptons and light active neutrinos

$$M_U = \begin{pmatrix} \widetilde{\varepsilon}_{11}^{(u)} & \varepsilon_{12}^{(u)} & \kappa_{13}^{(u)} \\ \widetilde{\varepsilon}_{12}^{(u)} & \varepsilon_{22}^{(u)} & \kappa_{23}^{(u)} \\ \widetilde{\varepsilon}_{13}^{(u)} & \varepsilon_{32}^{(u)} & \kappa_{33}^{(u)} \end{pmatrix} \frac{v}{\sqrt{2}}, \quad M_D = \begin{pmatrix} \widetilde{\varepsilon}_{11}^{(d)} & \widetilde{\varepsilon}_{12}^{(d)} & \varepsilon_{13}^{(d)} \\ \widetilde{\varepsilon}_{21}^{(d)} & \widetilde{\varepsilon}_{22}^{(d)} & \varepsilon_{23}^{(d)} \\ \widetilde{\varepsilon}_{31}^{(d)} & \widetilde{\varepsilon}_{32}^{(d)} & \varepsilon_{33}^{(d)} \end{pmatrix} \frac{v}{\sqrt{2}},$$

$$M_l = \begin{pmatrix} \widetilde{\varepsilon}_{11}^{(l)} & \varepsilon_{12}^{(l)} & \varepsilon_{13}^{(l)} \\ \widetilde{\varepsilon}_{21}^{(l)} & \varepsilon_{22}^{(l)} & \varepsilon_{23}^{(l)} \\ \widetilde{\varepsilon}_{31}^{(l)} & \varepsilon_{32}^{(l)} & \varepsilon_{33}^{(l)} \end{pmatrix} \frac{v}{\sqrt{2}}, \quad M_\nu = \begin{pmatrix} \varepsilon_{11}^{(\nu)} & \varepsilon_{12}^{(\nu)} & \varepsilon_{13}^{(\nu)} \\ \varepsilon_{12}^{(\nu)} & \varepsilon_{22}^{(\nu)} & \varepsilon_{23}^{(\nu)} \\ \varepsilon_{13}^{(\nu)} & \varepsilon_{23}^{(\nu)} & \varepsilon_{33}^{(\nu)} \end{pmatrix} \frac{v^2}{\sqrt{2}\,\Lambda},$$

their entries are generated at different loop-levels:

$$\kappa_{j3}^{(u)} \rightarrow \text{tree-level} \tag{13}$$

$$\varepsilon_{j2}^{(u)}, \varepsilon_{j3}^{(d)}, \varepsilon_{j2}^{(l)}, \varepsilon_{j3}^{(l)} \rightarrow \text{1-loop-level} \tag{14}$$

$$\widetilde{\varepsilon}_{j1}^{(u)}, \widetilde{\varepsilon}_{j1}^{(d)}, \widetilde{\varepsilon}_{j2}^{(d)}, \widetilde{\varepsilon}_{j1}^{(l)} \rightarrow \text{2-loop-level} \tag{15}$$

$$\varepsilon_{jk}^{(\nu)} \rightarrow \text{4-loop-level,} \tag{16}$$

where $j, k = 1, 2, 3$.

The $S_3 \times Z_2$ discrete group is assumed to be softly broken.

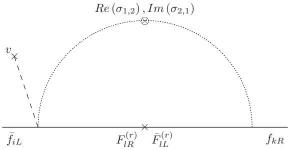
$$\phi \sim (\mathbf{1}, 1), \qquad \sigma = (\sigma_1, \sigma_2) \sim (\mathbf{2}, 1), \qquad \eta \sim (\mathbf{1}, -1), \tag{17}$$

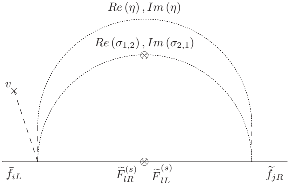
$$\begin{aligned}
u_{1R} &\sim (\mathbf{1}', -1), \quad u_{2R} \sim (\mathbf{1}', 1), \quad u_{3R} \sim (\mathbf{1}, 1), \\
d_{1R} &\sim (\mathbf{1}', -1), \quad d_{2R} \sim (\mathbf{1}', -1), \quad d_{3R} \sim (\mathbf{1}', 1), \\
l_{1R} &\sim (\mathbf{1}', -1), \quad l_{2R} \sim (\mathbf{1}', 1), \quad l_{3R} \sim (\mathbf{1}', 1), \\
q_{jL} &\sim (\mathbf{1}, 1), \quad l_{jL} \sim (\mathbf{1}, 1), \quad j = 1, 2, 3, \quad \nu_{sR} = (\mathbf{1}', -1), \quad s = 1, 2,
\end{aligned}$$

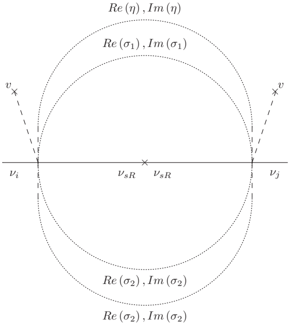
$$\begin{aligned}
T_L &= (T_{1L}, T_{2L}) \sim (\mathbf{2}, 1), \quad T_R = (T_{1R}, T_{2R}) \sim (\mathbf{2}, 1), \\
\widetilde{T}_L &= \left(\widetilde{T}_{1L}, \widetilde{T}_{2L}\right) \sim (\mathbf{2}, 1), \quad \widetilde{T}_R = \left(\widetilde{T}_{1R}, \widetilde{T}_{2R}\right) \sim (\mathbf{2}, -1), \\
B_L &= (B_{1L}, B_{2L}) \sim (\mathbf{2}, 1), \quad B_R = (B_{1R}, B_{2R}) \sim (\mathbf{2}, 1), \\
\widetilde{E}_L &= \left(\widetilde{E}_{1L}, \widetilde{E}_{2L}\right) \sim (\mathbf{2}, 1), \quad \widetilde{E}_R = \left(\widetilde{E}_{1R}, \widetilde{E}_{2R}\right) \sim (\mathbf{2} - 1), \\
\widetilde{B}_L^{(s)} &= \left(\widetilde{B}_{1L}^{(s)}, \widetilde{B}_{2L}^{(s)}\right) \sim (\mathbf{2}, 1), \quad \widetilde{B}_R^{(s)} = \left(\widetilde{B}_{1R}^{(s)}, \widetilde{B}_{2R}^{(s)}\right) \sim (\mathbf{2}, -1), \\
E_L^{(s)} &= \left(E_{1L}^{(s)}, E_{2L}^{(s)}\right) \sim (\mathbf{2}, 1), \quad E_R^{(s)} = \left(E_{1R}^{(s)}, E_{2R}^{(s)}\right) \sim (\mathbf{2}, 1).
\end{aligned} \tag{18}$$

$$
\begin{aligned}
-\mathcal{L}_{\mathrm{Y}}^{(U)} \;&=\; \sum_{j=1}^{3} y_j^{(u)} \overline{q}_{jL} \widetilde{\phi} \left( \widetilde{T}_R \sigma \right)_{\mathbf{1}} \frac{\eta}{\Lambda^2} + x^{(u)} \left( \overline{\widetilde{T}}_L \sigma \right)_{\mathbf{1}'} u_{1R} \frac{\eta}{\Lambda} \\
&+ \sum_{j=1}^{3} z_j^{(u)} \overline{q}_{jL} \widetilde{\phi} \left( T_R \sigma \right)_{\mathbf{1}} \frac{1}{\Lambda} + w^{(u)} \left( \overline{T}_L \sigma \right)_{\mathbf{1}'} u_{2R} \\
&+ \sum_{j=1}^{3} y_{j3}^{(u)} \overline{q}_{jL} \widetilde{\phi} u_{3R} + y_T \left( \overline{T}_L T_R \right)_{\mathbf{2}} \sigma + h.c.
\end{aligned}
$$

$$
\begin{aligned}
-\mathcal{L}_{\mathrm{Y}}^{(D)} \;&=\; \sum_{j=1}^{3} \sum_{s=1}^{2} y_{js}^{(d)} \overline{q}_{jL} \phi \left( \widetilde{B}_R^{(s)} \sigma \right)_{\mathbf{1}} \frac{\eta}{\Lambda^2} + \sum_{s=1}^{2} \sum_{k=1}^{2} x_{sk}^{(d)} \left( \overline{\widetilde{B}}_L^{(s)} \sigma \right)_{\mathbf{1}'} d_{kR} \frac{\eta}{\Lambda} \\
&+ \sum_{j=1}^{3} z_j^{(d)} \overline{q}_{jL} \phi \left( B_R \sigma \right)_{\mathbf{1}} \frac{1}{\Lambda} + w^{(d)} \left( \overline{B}_L \sigma \right)_{\mathbf{1}'} d_{3R} \\
&+ y_B \left( \overline{B}_L B_R \right)_{\mathbf{2}} \sigma + h.c.
\end{aligned}
$$


$Re\,(\sigma_{1,2})\,,Im\,(\sigma_{2,1})$
$v$
$\bar{f}_{iL}$
$F_{lR}^{(r)}$
$\bar{F}_{lL}^{(r)}$
$f_{kR}$


$Re\,(\eta)\,,Im\,(\eta)$
$Re\,(\sigma_{1,2})\,,Im\,(\sigma_{2,1})$
$v$
$\bar{f}_{iL}$
$\widetilde{F}_{lR}^{(s)}$
$\bar{\widetilde{F}}_{lL}^{(s)}$
$\widetilde{f}_{jR}$


$Re\,(\eta)\,,Im\,(\eta)$
$Re\,(\sigma_1)\,,Im\,(\sigma_1)$
$v$
$v$
$\nu_i$
$\nu_{sR}$
$\nu_{sR}$
$\nu_j$
$Re\,(\sigma_2)\,,Im\,(\sigma_2)$
$Re\,(\sigma_2)\,,Im\,(\sigma_2)$

$$-\mathcal{L}_Y^{(l)} = \sum_{j=1}^{3} y_j^{(l)} \bar{l}_{jL}\phi\left(\widetilde{E}_R\sigma\right)_{\mathbf{1}}\frac{\eta}{\Lambda^2} + x_1^{(l)}\left(\overline{\widetilde{E}}_L\sigma\right)_{\mathbf{1}'} l_{1R}\frac{\eta}{\Lambda}$$

$$+\sum_{j=1}^{3}\sum_{s=1}^{2} y_{js}^{(l)}\bar{l}_{jL}\phi\left(E_R^{(s)}\sigma\right)_{\mathbf{1}}\frac{1}{\Lambda} + \sum_{k=1}^{2}\sum_{s=1}^{2} x_{ks}^{(l)}\left(\overline{E}_L^{(s)}\sigma\right)_{\mathbf{1}'} l_{kR}$$

$$+\sum_{s=1}^{2} y_s^{(E)}\left(\overline{E}_L^{(s)}E_R^{(s)}\right)_{\mathbf{2}}\sigma + h.c.,$$

$$-\mathcal{L}_Y^{(\nu)} = \sum_{j=1}^{3}\sum_{s=1}^{2} y_{js}^{(\nu)}\bar{l}_{jL}\widetilde{\phi}\nu_{sR}\frac{\left[\sigma\left(\sigma\sigma\right)_{\mathbf{2}}\right]_{\mathbf{1}'}\eta}{\Lambda^4} + \sum_{s=1}^{2} m_s\bar{\nu}_{sR}\nu_{sR}^C + h.c.$$

$$\mathcal{L}_{soft}^F = \widetilde{m}_T\left(\overline{\widetilde{T}}_L\widetilde{T}_R\right)_{\mathbf{1}} + \sum_{s=1}^{2}\widetilde{m}_B^{(s)}\left(\overline{\widetilde{B}}_L^{(s)}\widetilde{B}_R^{(s)}\right)_{\mathbf{1}} + \widetilde{m}_E\left(\overline{\widetilde{E}}_L\widetilde{E}_R\right)_{\mathbf{1}} + h.c.\,, \quad (19)$$

$$\mathcal{L}_{soft}^{\sigma} = \mu_{12}^2\sigma_1\sigma_2 \quad (20)$$

$$m_b \sim \frac{y_b^2}{16\pi^2} f_1 \frac{v}{\Lambda} \frac{\mu_{12}}{M} \mu_{12}, \tag{21}$$

$$m_s \sim \frac{y_s^2}{(16\pi^2)^2} f_2 \frac{v}{M} \frac{\mu_{12}^3}{\Lambda^3} \mu_{12}, \tag{22}$$

Assuming $y_b^2 f_1 \sim y_s^2 f_2 \sim 1$ and $\mu_{12} \sim M$, we find a rough estimate

$$\Lambda \sim 10v \sim 2.5\mathrm{TeV} \tag{23}$$

for the correct order of magnitude of $m_b$ and $m_s$.

# Model Phenomenology.

$$M_\nu = \frac{\mu_\eta^2 \mu_\sigma^6 v}{(16\pi^2)^4 \Lambda^8} \begin{pmatrix} \beta_1^2+\gamma_1^2 & \beta_1\beta_2+\gamma_1\gamma_2 & \beta_1\beta_3+\gamma_1\gamma_3 \\ \beta_1\beta_2+\gamma_1\gamma_2 & \beta_2^2+\gamma_2^2 & \beta_2\beta_3+\gamma_2\gamma_3 \\ \beta_1\beta_3+\gamma_1\gamma_3 & \beta_2\beta_3+\gamma_2\gamma_3 & \beta_3^2+\gamma_3^2 \end{pmatrix},$$

$$\beta_s = y_{s1}^{(\nu)} \frac{v}{m_1} f_1^{(\nu)}, \quad \gamma_s = y_{s2}^{(\nu)} \frac{v}{m_2} f_2^{(\nu)}, \quad s=1,2. \tag{24}$$

$$m_\nu \sim \frac{\left(y^{(\nu)}\right)^2}{(16\pi^2)^4} f^{(\nu)} \frac{v}{m_s} \frac{\mu_\eta^2 \mu_\sigma^6}{\Lambda^8} v. \tag{25}$$

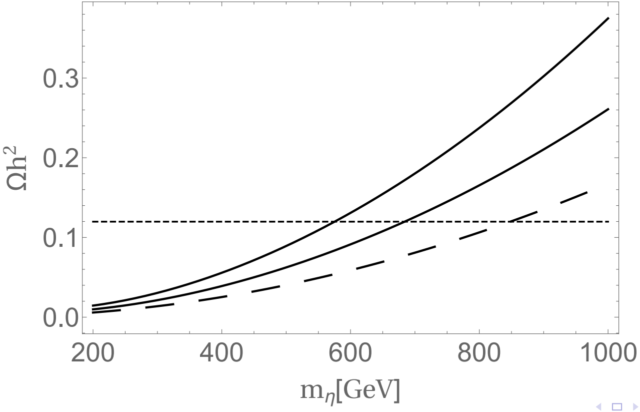
Assuming $\left(y^{(\nu)}\right)^2 \cdot f^{(\nu)} \sim 1$, $\mu_\eta \sim \mu_\sigma \sim m_s \sim \alpha \cdot \Lambda$ and taking $\Lambda = 2.5$TeV from the quark sector (23) we find for $\alpha \sim 1$ the light neutrino mass scale $m_\nu \sim 1$eV, which is too heavy. Assuming, for instance, $\alpha = 0.3$ we arrive at the correct neutrino mass scale $m_\nu \sim 50$ meV. We expect a typical mass scale for all the non-SM particles – the $\eta$-DM candidate, in particular, – to be $m_{\mathrm{non-SM}} \sim m_\eta \sim \alpha \cdot \Lambda \sim 750$ GeV.

The only possible decay modes of $\eta$ are

$$\begin{aligned}\eta \quad \rightarrow \quad & \sigma_{1,2}\widetilde{T}_{2L,1L}u_{1R},\ \sigma_{1,2}\widetilde{T}_{1R,2R}u_{iL},\ \sigma_{1,2}\widetilde{B}^{(s)}_{2L,1L}d_{kR},\ \sigma_{1,2}\widetilde{B}^{(s)}_{1R,2R}d_{iL}, \\ & \sigma_{1,2}\widetilde{E}_{2L,1L}l_{1R},\ \sigma_{1,2}\widetilde{E}_{1R,2R}e_{iL},\ \sigma_1 2\sigma_2\nu_{iL}\nu_{sR} \end{aligned} \tag{26}$$

with $s, k = 1, 2$ and $i = 1, 2, 3$.

We assume that our DM candidate $\eta$ annihilates mainly into $WW$, $ZZ$, $t\bar{t}$, $b\bar{b}$ and $hh$. We take $\lambda_{h^2\eta^2} = 1, 1.2, 1.5$ (from top to bottom, respectively).



# Conclusions

For the $S_3 \times Z_8$ flavor model:

- The top quark and the exotic fermions acquire tree level masses.
- The remaining charged fermions and the light active neutrinos get one and three loop level masses, respectively.
- The breaking of $Z_8$ generates the non SM fermion masses as well as the observed pattern of SM fermion masses and mixings
- The preserved $S_3$ allows for natural dark matter candidates.

For the $S_3 \times Z_2$ flavor model:

- The SM fermion mass hierarchy is generated by the loops.
- We model cutoff scale is $\Lambda \sim 2.5$ TeV, from the 1- and 2-loop quark masses.
- The model predicts one massless and two non-zero mass neutrinos.
- We hinted that the mass scale of the non-SM particles of our model are of the order of 1 TeV.
- The model possesses DM particle candidates. We found that one of them, the SM-singlet scalar $\eta$ lighter than the other non-SM scalars, could be a viable DM particle.

# Acknowledgements

Thank you very much to all of you for the attention.

A.E.C.H thanks the Organizers of Planck 2017 for inviting him to present this talk and hosting a very nice Conference.

A.E.C.H was supported by Fondecyt (Chile), Grant No. 1170803.

# Extra Slides

Since the dimensionless parameters $\varepsilon_{jk}^{(f)}$ $(j,k=1,2,3)$ with $f=u,d,l$, are generated at one loop level, I set $\varepsilon_{jk}^{(f)}=a_{jk}^{(f)}\lambda^3$. In addition, I adopt the benchmark:

$$\begin{aligned} a_{12}^{(u)} &= a_{21}^{(u)}, \qquad a_{31}^{(u)}=y_{13}^{(u)}, \qquad a_{32}^{(u)}=y_{23}^{(u)} \\ a_{12}^{(d)} &= \left|a_{12}^{(d)}\right| e^{-i\tau_1}, \qquad a_{21}^{(d)}=\left|a_{12}^{(d)}\right| e^{i\tau_1}, \\ a_{13}^{(d)} &= \left|a_{13}^{(d)}\right| e^{-i\tau_2}, \qquad a_{31}^{(d)}=\left|a_{13}^{(d)}\right| e^{i\tau_2}, \qquad a_{23}^{(d)}=a_{32}^{(d)}. \end{aligned} \tag{27}$$

The best fit values are:

$$\begin{aligned} a_{11}^{(u)} &\simeq 0.58, \qquad a_{22}^{(u)}\simeq 2.19, \qquad a_{12}^{(u)}\simeq 0.67, \\ a_{13}^{(u)} &\simeq 0.80, \qquad a_{23}^{(u)}\simeq 0.83, \qquad a_{11}^{(d)}\simeq 1.96, \\ a_{12}^{(d)} &\simeq 0.53, \qquad a_{13}^{(d)}\simeq 1.07, \qquad a_{22}^{(d)}\simeq 1.93, \\ a_{23}^{(d)} &\simeq 1.36, \qquad a_{33}^{(d)}\simeq 1.35, \qquad \tau_1\simeq 9.56^\circ, \qquad \tau_2\simeq 4.64^\circ. \end{aligned} \tag{28}$$

| Observable | Model value | Experimental value |
| --- | --- | --- |
| $m_u(MeV)$ | 1.44 | $1.45^{+0.56}_{-0.45}$ |
| $m_c(MeV)$ | 656 | $635 \pm 86$ |
| $m_t(GeV)$ | 177.1 | $172.1 \pm 0.6 \pm 0.9$ |
| $m_d(MeV)$ | 2.9 | $2.9^{+0.5}_{-0.4}$ |
| $m_s(MeV)$ | 57.7 | $57.7^{+16.8}_{-15.7}$ |
| $m_b(GeV)$ | 2.82 | $2.82^{+0.09}_{-0.04}$ |
| $\sin\theta_{12}$ | 0.225 | 0.225 |
| $\sin\theta_{23}$ | 0.0412 | 0.0412 |
| $\sin\theta_{13}$ | 0.00351 | 0.00351 |
| $\delta$ | $64^\circ$ | $68^\circ$ |

Table: Model and experimental values of the quark masses and CKM parameters.

In the concerning to the charged lepton sector, I adopt the benchmark $a_{jk}^{(l)} = a_k^{(l)}\delta_{jk}$, so that the charged lepton masses take the form:

$$m_e = a_1^{(l)}\lambda^7\frac{v}{\sqrt{2}}, \qquad m_\mu = a_2^{(l)}\lambda^5\frac{v}{\sqrt{2}}, \qquad m_\tau = a_3^{(l)}\lambda^3\frac{v}{\sqrt{2}}.$$

The best-fit values are:

$$\begin{aligned} \varrho = \varphi/2 &\simeq 38.73^\circ, \quad W_1 \simeq -0.063eV^{\frac{1}{2}}, \quad W_2 \simeq 0.18eV^{\frac{1}{2}}, \\ W_3 &\simeq 0.15eV^{\frac{1}{2}}, \quad \text{for NH} \\ a_1^{(l)} &\simeq 0.1, \quad a_2^{(l)} \simeq 1.02, \quad a_3^{(l)} \simeq 0.88, \end{aligned} \tag{29}$$

$$\begin{aligned} \varrho &\simeq 162.26^\circ, \quad \varphi \simeq 79.44^\circ, \quad W_1 \simeq 0.22eV^{\frac{1}{2}}, \\ W_2 &\simeq 0.15eV^{\frac{1}{2}}, \quad W_3 \simeq 0.17eV^{\frac{1}{2}}, \quad \text{for IH} \\ a_1^{(l)} &\simeq 0.1, \quad a_2^{(l)} \simeq 1.02, \quad a_3^{(l)} \simeq 0.88, \end{aligned} \tag{30}$$

| Observable | Model value | Experimental value |
|---|---|---|
| $m_e(MeV)$ | 0.487 | 0.487 |
| $m_\mu(MeV)$ | 102.8 | $102.8 \pm 0.0003$ |
| $m_\tau(GeV)$ | 1.75 | $1.75 \pm 0.0003$ |
| $\Delta m_{21}^2(10^{-5}\text{eV}^2)$ (NH) | 7.22 | $7.60^{+0.19}_{-0.18}$ |
| $\Delta m_{31}^2(10^{-3}\text{eV}^2)$ (NH) | 2.50 | $2.48^{+0.05}_{-0.07}$ |
| $\sin^2\theta_{12}$ (NH) | 0.334 | $0.323 \pm 0.016$ |
| $\sin^2\theta_{23}$ (NH) | 0.567 | $0.567^{+0.032}_{-0.128}$ |
| $\sin^2\theta_{13}$ (NH) | 0.0228 | $0.0234 \pm 0.0020$ |
| $\Delta m_{21}^2(10^{-5}\text{eV}^2)$ (IH) | 7.60 | $7.60^{+0.19}_{-0.18}$ |
| $\Delta m_{13}^2(10^{-3}\text{eV}^2)$ (IH) | 2.48 | $2.48^{+0.05}_{-0.06}$ |
| $\sin^2\theta_{12}$ (IH) | 0.323 | $0.323 \pm 0.016$ |
| $\sin^2\theta_{23}$ (IH) | 0.573 | $0.573^{+0.025}_{-0.043}$ |
| $\sin^2\theta_{13}$ (IH) | 0.0240 | $0.0240 \pm 0.0019$ |

Table: Model and experimental values of the charged lepton masses, neutrino mass squared splittings and leptonic mixing parameters for the normal (NH) and inverted (IH) mass hierarchies.

For the second model, we adopt the benchmark:

$$\begin{aligned} \widetilde{\varepsilon}^{(u)}_{i1} &= a^{(u)}_i \lambda^8, \qquad \varepsilon^{(u)}_{i2} = b^{(u)}_i \lambda^4, \qquad \widetilde{\varepsilon}^{(d)}_{i1} = a^{(d)}_i \lambda^8 \\ \widetilde{\varepsilon}^{(d)}_{i2} &= a^{(d)}_i \lambda^6, \qquad \varepsilon^{(d)}_{i3} = a^{(d)}_i \lambda^3, \qquad i = 1,2,3. \end{aligned} \tag{31}$$

The best fit values are:

$$\begin{aligned} a^{(u)}_1 &\simeq 2.17, \qquad a^{(u)}_2 \simeq 1.01, \qquad a^{(u)}_3 \simeq 0.51, \qquad b^{(u)}_1 \simeq 1.63, \\ b^{(u)}_2 &\simeq 0.40, \qquad b^{(u)}_3 \simeq 2.45, \qquad \kappa^{(u)}_{13} = \kappa^{(u)}_{23} = \kappa^{(u)}_{33} \simeq 0.57, \\ a^{(d)}_1 &\simeq -2.04 - 4.60 \times 10^{-3} i, \qquad a^{(d)}_2 \simeq 1.20 - 4.88 \times 10^{-3} i, \\ b^{(d)}_1 &\simeq -0.17 - 1.08 \times 10^{-3} i, \qquad b^{(d)}_2 \simeq -1.60 - 1.14 \times 10^{-3} i, \\ c^{(d)}_1 &\simeq -0.81 - 3.78 \times 10^{-3} i, \qquad c^{(d)}_2 \simeq -0.86 + 1.51 \times 10^{-3}, \\ a^{(d)}_3 &\simeq 0.81 - 4.42 \times 10^{-3} i, \qquad b^{(d)}_3 \simeq 1.95 - 1.03 \times 10^{-3} i, \\ c^{(d)}_3 &\simeq -0.78 + 2.27 \times 10^{-3} i \end{aligned} \tag{32}$$

| Observable | Model value | Experimental value |
|---|---|---|
| $m_u(\mathrm{MeV})$ | 1.37 | $1.45^{+0.56}_{-0.45}$ |
| $m_c(\mathrm{MeV})$ | 652 | $635 \pm 86$ |
| $m_t(\mathrm{GeV})$ | 172 | $172.1 \pm 0.6 \pm 0.9$ |
| $m_d(\mathrm{MeV})$ | 2.9 | $2.9^{+0.5}_{-0.4}$ |
| $m_s(\mathrm{MeV})$ | 57.7 | $57.7^{+16.8}_{-15.7}$ |
| $m_b(\mathrm{GeV})$ | 2.82 | $2.82^{+0.09}_{-0.04}$ |
| $\sin\theta_{12}$ | 0.22536 | $0.22536 \pm 0.00061$ |
| $\sin\theta_{23}$ | 0.0414 | $0.0414 \pm 0.0012$ |
| $\sin\theta_{13}$ | 0.00355 | $0.00355 \pm 0.00015$ |
| $\delta$ | $68^\circ$ | $68^\circ$ |

Table: Model and experimental values of the quark masses and CKM parameters.