Scotogenic dark matter and single-zero textures of the neutrino mass matrix

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Backgroud

Two crucial problems : (1) Origin of neutrino masses and mixing pattern (2) Dark matter

Texture one zero

A simplest pattern of neutrino mass matrix

$$M_\nu = \begin{pmatrix} M_{ee} & M_{e\mu} & M_{e\tau} \\ - & M_{\mu\mu} & M_{\mu\tau} \\ - & - & M_{\tau\tau} \end{pmatrix}$$

For examples
Xing, PRD69 (2004)
Bora et.al., PRD96 (2017)

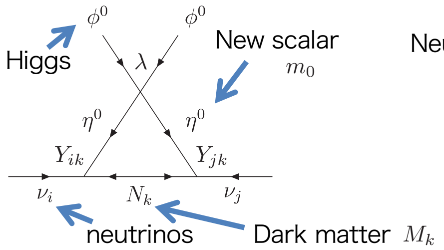
$$G_1 : \begin{pmatrix} 0 & \times & \times \\ - & \times & \times \\ - & - & \times \end{pmatrix} \quad G_2 : \begin{pmatrix} \times & 0 & \times \\ - & \times & \times \\ - & - & \times \end{pmatrix} \quad G_3 : \begin{pmatrix} \times & \times & 0 \\ - & \times & \times \\ - & - & \times \end{pmatrix}$$

$$G_4 : \begin{pmatrix} \times & \times & \times \\ - & 0 & \times \\ - & - & \times \end{pmatrix} \quad G_5 : \begin{pmatrix} \times & \times & \times \\ - & \times & 0 \\ - & - & \times \end{pmatrix} \quad G_6 : \begin{pmatrix} \times & \times & \times \\ - & \times & \times \\ - & - & 0 \end{pmatrix}$$

Scotogenic model

Ma, PRD73 (2006)

Simultaneously account for the presence of dark matter and the origin of neutrino masses



Neutrino sector — Dark sector

$$M_{\alpha\beta} = \sum_{k=1}^{3} Y_{\alpha k} Y_{\beta k} \Lambda_k$$

Yukawa couplings

Texture one zero & socotogenic model with real Yukawa couplings -> G_3

G_1,G_4,G_6 : excluded

$$G_1 : \begin{pmatrix} 0 & \times & \times \\ - & \times & \times \\ - & - & \times \end{pmatrix}$$

$$M_{ee} = Y_{e1}^2\Lambda_1 + Y_{e2}^2\Lambda_2 + Y_{e3}^2\Lambda_3 = 0$$

$$\Lambda_k \sim \frac{\lambda M_k}{m_0^2 - M_k^2}\left(1 - \frac{M_k^2}{m_0^2 - M_k^2}\ln\frac{m_0^2}{M_k^2}\right) > 0$$

Assumption 1 : Real Yukawa couplings

$$Y_{e1} = Y_{e2} = Y_{e3} = 0$$

$$M_{e\mu} = \sum_{k=1}^{3} Y_{ek}Y_{\mu k}\Lambda_k = 0$$

$$M_{e\tau} = \sum_{k=1}^{3} Y_{ek}Y_{\tau k}\Lambda_k = 0$$

$$M_\nu = \begin{pmatrix} M_{ee} & M_{e\mu} & M_{e\tau} \\ - & M_{\mu\mu} & M_{\mu\tau} \\ - & - & M_{\tau\tau} \end{pmatrix}$$

$$\begin{pmatrix} 0 & 0 & 0 \\ - & \times & \times \\ - & - & \times \end{pmatrix}$$

Violation of one zero texture

$$G_1 : \begin{pmatrix} 0 & \times & \times \\ - & \times & \times \\ - & - & \times \end{pmatrix}$$

excluded

$$G_4 : \begin{pmatrix} \times & \times & \times \\ - & 0 & \times \\ - & - & \times \end{pmatrix} \rightarrow \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & 0 \\ - & 0 & \times \end{pmatrix}$$

excluded

$$M_{\mu\mu} = Y_{\mu1}^2\Lambda_1 + Y_{\mu2}^2\Lambda_2 + Y_{\mu3}^2\Lambda_3 = 0$$

$$Y_{\mu1} = Y_{\mu2} = Y_{\mu3} = 0$$

$$G_6 : \begin{pmatrix} \times & \times & \times \\ - & \times & \times \\ - & - & 0 \end{pmatrix} \rightarrow \begin{pmatrix} \times & \times & 0 \\ - & \times & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

excluded

$$M_{\tau\tau} = Y_{\tau1}^2\Lambda_1 + Y_{\tau2}^2\Lambda_2 + Y_{\tau3}^2\Lambda_3 = 0$$

$$Y_{\tau1} = Y_{\tau2} = Y_{\tau3} = 0$$

Parameters

$$M_{\alpha\beta} = \sum_{k=1}^{3} Y_{\alpha k} Y_{\beta k} \Lambda_k \qquad \Lambda_k \sim \frac{\lambda}{m_0}\frac{r_k}{1-r_k^2}\left(1 - \frac{r_k^2}{1-r_k^2}\ln\frac{1}{r_k^2}\right) \qquad r_k = \frac{M_k}{m_0}$$

9 param in Y — 5 param in Λ

9 param in Y

From observation of neutrino mixing angles 9 -> 3 param

$$Y = \begin{pmatrix} Y_{e1} & Y_{e2} & Y_{e3} \\ Y_{\mu1} & Y_{\mu2} & Y_{\mu3} \\ Y_{\tau1} & Y_{\tau2} & Y_{\tau3} \end{pmatrix} = \begin{pmatrix} Y_1 & Y_2 & Y_3 \\ -0.647Y_1 & Y_2 & 4.40Y_3 \\ 0.343Y_1 & -Y_2 & 5.39Y_3 \end{pmatrix}$$

Singirala, CPC41 (2017)

Assumption 2 : Normal ordering of neutrino masses 3 -> 1 param, Y_1

Salas et.al., PLB782 (2018)

Normal

$$m_{\nu1} < m_{\nu2} < m_{\nu3}$$

Inverted

$$m_{\nu3} < m_{\nu1} \lesssim m_{\nu2}$$

$$Y_2^2 = \frac{1}{3.00\Lambda_1}\sqrt{\Delta m_{21}^2 + (1.54Y_1^2\Lambda_1)^2}$$

$$Y_3^2 = \frac{1}{49.4\Lambda_3}\sqrt{\Delta m_{31}^2 + (1.54Y_1^2\Lambda_1)^2}$$

$$\Delta m_{21}^2 = 7.50\times10^{-3}\mathrm{eV}^2 \qquad \Delta m_{31}^2 = 2.53\times10^{-5}\mathrm{eV}^2$$

Texture one zero — Y_1 is function of Λ

$$M_{e\tau} = Y_{e1}Y_{\tau1}\Lambda_1 + Y_{e2}Y_{\tau2}\Lambda_2 + Y_{e3}Y_{\tau3}\Lambda_3$$
$$= 0.343Y_1^2\Lambda_1 - Y_2^2\Lambda_1 + 5.39Y_3^2\Lambda_3$$
$$= 0.343Y_1^2\Lambda_1 + \frac{1}{3}\sqrt{\Delta m_{21}^2 + (1.54Y_1^2\Lambda_1)^2} + \frac{5.39}{49.4}\sqrt{\Delta m_{31}^2 + (1.54Y_1^2\Lambda_1)^2} = 0$$

Ex) $G_3 : \begin{pmatrix} \times & \times & 0 \\ - & \times & \times \\ - & - & \times \end{pmatrix}$

5 param in Λ

$$3.6\times10^{-9} \le \lambda \le 4.2\times10^{-9} \qquad 2 \le m_0[\mathrm{TeV}] \le 4 \qquad 0.5 \le r_1 \le 0.99 \qquad 1.1 \le r_3 \le 3.0 \qquad r_1 = r_2$$

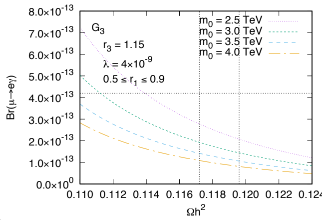
Kubo et.al, PLB642 (2006) — Ibarra et.al., PRD93 (2016) — Lindner et.al., PRD94 (2016)

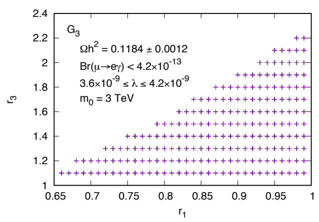
G_3 is consistent with observations

Dark matter $\Omega h^2 = 0.1184 \pm 0.0012$ — Planck, A&A594 (2016)

LFV $\mathrm{Br}(\mu\to e\gamma) \le 4.2\times10^{-13}$ — NEG, EPJC104 (2016)

Neutrino oscillation $3\ \sigma$ — Esteban, et.al, JHEP (2017)





$$G_2 : \begin{pmatrix} \times & 0 & \times \\ - & \times & \times \\ - & - & \times \end{pmatrix}$$

excluded

$$G_3 : \begin{pmatrix} \times & \times & 0 \\ - & \times & \times \\ - & - & \times \end{pmatrix}$$

consistent

$$G_5 : \begin{pmatrix} \times & \times & \times \\ - & \times & 0 \\ - & - & \times \end{pmatrix}$$

excluded

Summary

Texture one zero
6 candidates

&

Scotogenic model

Real Yukawa couplings — Dark matter abundance

ν : Normal ordering, 3σ — LFV : $\mu \to e\gamma$

-> $G_3 : \begin{pmatrix} \times & \times & 0 \\ - & \times & \times \\ - & - & \times \end{pmatrix}$

Future plan

Complex Yukawa coupling
(including CP violating phases)