The Impact Of Dark Matter On The Related Sector Of The Scotogenic Model And Its Implications

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Outline

* The Scotogenic model

* neutrino mass generation and Dark Matter

* Constraints from low energy and dark matter data

The scotogenic model is a possible extension of the standard model (SM), which allows to generate neutrino masses while providing viable dark matter candidates.

Particle contenet- DM candidates

* One scalar doublet, η

* three singlet majorana fermions, N_k

* both η and N_k are odd under an exactly conserved Z_2 symmetry.

*SM particles are even under Z_2.

* being Z_2 odd, the lightest one of the new particles is stable and can serve as a dark matter (DM) candidate.

* Many options for the DM candidate have been explored:

fermionic dark matter:
- N_1 being the DM

- N_1 and N_2 are nearly degenerate and play the role of DM

scalar dark matter: the real component of the new scalar doublet

we shall choose N_1 to be the DM.

* Neutrino mass is generated radiatively at the one-loop level.

INTERACTIONS OF NEW SCALARS

The interaction of the scalar particles with each other and the SM gauge bosons, W_ρ and B_ρ, are described by

$$\mathcal{L} = (\mathcal{D}^\rho \Phi)^\dagger \mathcal{D}_\rho \Phi + (\mathcal{D}^\rho \eta)^\dagger \mathcal{D}_\rho \eta - \mathcal{V}$$

$$\mathcal{D}_\rho = \partial_\rho + ig\frac{\mathcal{T}}{2} W_\rho + ig_Y Q_Y B_\rho$$

$$\mathcal{V} = \mu_1^2 \Phi^\dagger\Phi + \mu_2^2 \eta^\dagger\eta + \frac{1}{2}\lambda_1 (\Phi^\dagger\Phi)^2 + \frac{1}{2}\lambda_2 (\eta^\dagger\eta)^2 + \lambda_3 (\Phi^\dagger\Phi)(\eta^\dagger\eta) + \lambda_4 (\Phi^\dagger\eta)(\eta^\dagger\Phi) + \frac{1}{2}\lambda_5 [(\Phi^\dagger\eta)^2 + (\eta^\dagger\Phi)^2]$$

After electroweak symmetry breaking

$$\Phi = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(h + v) \end{pmatrix} \quad , \quad \eta = \begin{pmatrix} \mathrm{H}^+ \\ \frac{1}{\sqrt{2}}(S + i\mathcal{P}) \end{pmatrix}$$

v is the vacuum expectation value (VEV) of Φ. The VEV of η is zero due to the Z_2 symmetry

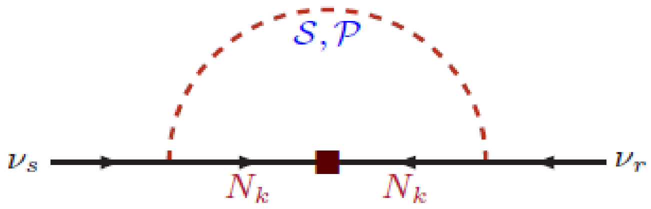
The new singlet fermions N_k are permitted to have Majorana masses and interact with other particles according to

$$\mathcal{L}_N = -\frac{1}{2} M_k \overline{N_k^{\mathrm{c}}} P_R N_k + \mathcal{Y}_{jk} \left[\bar{\ell}_j H^- - \frac{1}{\sqrt{2}} \bar{\nu}_j (\mathcal{S} - i\mathcal{P}) \right] P_R N_k \; + \mathrm{H.c.},$$

where $j, k = 1, 2, 3$ are summed over, the superscript c refers to charge conjugation, $P_R = \frac{1}{2}(1 + \gamma_5)$, and $\ell_{1,2,3} = e, \mu, \tau$. Hence, writing the Yukawa couplings $\mathcal{Y}_{jk} = Y_{\ell_j k}$,

$$\mathcal{Y} = \begin{pmatrix} Y_{e1} & Y_{e2} & Y_{e3} \\ Y_{\mu 1} & Y_{\mu 2} & Y_{\mu 3} \\ Y_{\tau 1} & Y_{\tau 2} & Y_{\tau 3} \end{pmatrix}.$$

Radiative Neutrino mass generation



Ma, 2006

$$(\mathcal{M}_\nu)_{ij} = \frac{\mathcal{Y}_{ik}\mathcal{Y}_{jk}M_k}{16\pi^2}\left(\frac{m_\mathcal{S}^2}{m_\mathcal{S}^2 - M_k^2}\ln\frac{m_\mathcal{S}^2}{M_k^2} - \frac{m_\mathcal{P}^2}{m_\mathcal{P}^2 - M_k^2}\ln\frac{m_\mathcal{P}^2}{M_k^2}\right)$$

$$\mathrm{diag}(m_1, m_2, m_3) = \mathcal{U}^\mathrm{T}\mathcal{M}_\nu\mathcal{U},$$

where $\mathcal{U}$ is the Pontecorvo-Maki-Nakagawa-Sakata unitary matrix and the expression for Λ_k is valid for $m_0 \simeq m_\mathcal{S} \simeq m_\mathcal{P}$.

$$\mathcal{M}_\nu = \mathcal{Y}\,\mathrm{diag}(\Lambda_1, \Lambda_2, \Lambda_3)\,\mathcal{Y}^\mathrm{T},$$

$$\Lambda_k = \frac{\lambda_5 v^2}{16\pi^2 M_k} I\left(\frac{M_k^2}{m_0^2}\right),$$

$$I(x) = \frac{x}{1-x} + \frac{x^2\ln x}{(1-x)^2},$$

$$2m_0^2 = m_\mathcal{S}^2 + m_\mathcal{P}^2,$$

$$\mathcal{U} = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\cos\theta\cos\varsigma & \sqrt{2}\sin\theta & \sqrt{2}e^{i\delta}\cos\theta\sin\varsigma \\ -\sin\theta\cos\varsigma - e^{-i\delta}\sin\varsigma & \cos\theta & -e^{i\delta}\sin\theta\sin\varsigma + \cos\varsigma \\ \sin\theta\cos\varsigma - e^{-i\delta}\sin\varsigma & -\cos\theta & e^{i\delta}\sin\theta\sin\varsigma + \cos\varsigma \end{pmatrix}.$$

$$Y_{e1} = \frac{\sqrt{2}c_\theta c_\varsigma Y_1}{s_\theta c_\varsigma - s_\varsigma}, \qquad Y_{e2} = \frac{-\sqrt{2}s_\theta Y_2}{c_\theta},$$

$$Y_{e3} = \frac{\sqrt{2}c_\theta s_\varsigma Y_3}{s_\theta s_\varsigma + c_\varsigma}, \qquad Y_{\mu 1} = \frac{s_\varsigma + s_\theta c_\varsigma}{s_\varsigma - s_\theta c_\varsigma} Y_1,$$

$$Y_{\mu 2} = -Y_2, \qquad Y_{\mu 3} = \frac{c_\varsigma - s_\theta s_\varsigma}{s_\theta s_\varsigma + c_\varsigma} Y_3,$$

$$m_1 = \frac{2\Lambda_1 Y_1^2}{(s_\varsigma - s_\theta c_\varsigma)^2}, \qquad m_2 = \frac{2\Lambda_2 Y_2^2}{c_\theta^2}, \qquad m_3 = \frac{2\Lambda_3 Y_3^2}{(c_\varsigma + s_\theta s_\varsigma)^2}.$$

These expressions for $m_{1;2;3}$ would permit cancellations among the terms in with larger Y_k than would the masses. Numerically, we adopt for definiteness

$$\Delta m_{ji}^2 = m_j^2 - m_i^2$$

$$\cos\theta \sin\varsigma = \sqrt{0.0227}, \qquad \theta = 32.89°,$$

The data on W and Z widths and the null results of direct searches for new particles at LEP imply that the inert scalar particles masses should satisfy

$$m_H + m_{\mathcal{S},\mathcal{P}} > m_W, \qquad m_H \gtrsim 70 \text{ GeV}, \qquad m_{\mathcal{S}} + m_{\mathcal{P}} > m_Z,$$

80 GeV $\leq m_{\mathcal{S}}$ and 100 GeV $\leq m_p$

the constraints from the EW precision data, which can be avoided by assuming the mass degeneracy between the charged and neutral inert scalars

At zero temperature, the inert scalar particles

should be heavier than the dark matter N, otherwise N becomes unstable and decays into the inert scalar particles

Fermionic Dark Matter: Scenario One: only one candidate

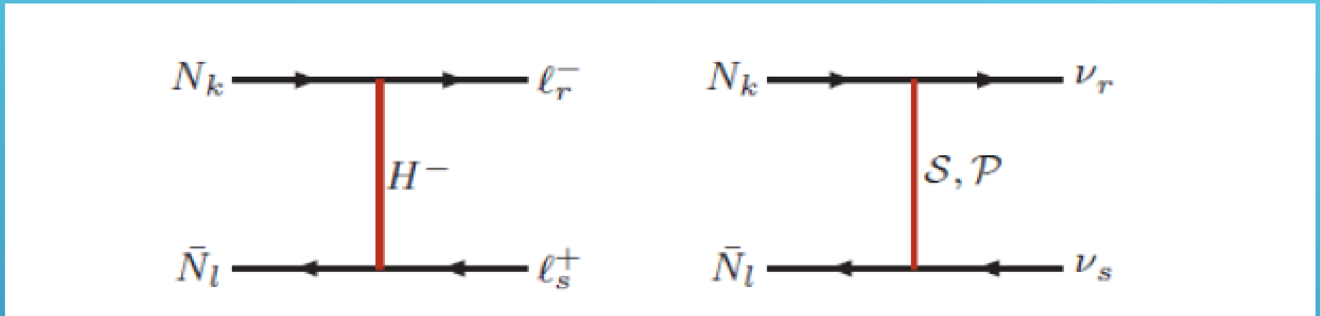
$$m_0 \simeq m_{\mathcal{S}} \simeq m_{\mathcal{P}}.$$

$$\sigma_{\text{ann}} v_{\text{rel}} = \sum_{i,j=1,2,3} \frac{|\mathcal{Y}_{i1}\mathcal{Y}_{j1}|^2 M_1^2 v_{\text{rel}}^2}{48\pi} \times \left[\frac{M_1^4 + m_H^4}{(M_1^2 + m_H^2)^4} + \frac{M_1^4 + m_0^4}{(M_1^2 + m_0^2)^4}\right]$$

$$\sigma_{\text{ann}} v_{\text{rel}} = a + b v_{\text{rel}}^2 + \mathcal{O}(v_{\text{rel}}^4)$$

$$\Omega \hat{h}^2 = \frac{1.07 \times 10^9 x_f \ \text{GeV}^{-1}}{\sqrt{g_*} m_{\text{Pl}} [a + 3(b - a/4)/x_f]},$$

$$x_f = \ln \frac{0.0955(a + 6b/x_f) M_1 m_{\text{Pl}}}{\sqrt{g_* x_f}},$$



$$\mathcal{Y}_{r1} \propto Y_1$$

- N_1 serve as cold DM, important constraints can be imposed on

$$x_f = \ln \frac{0.0955(a + 6b/x_f) M_1 m_{\text{Pl}}}{\sqrt{g_* x_f}},$$

DM Direct Detection Constraints

For the fermion dark matter N_1, the interactions with nucleons appear at the one-loop

the spin-independent cross-section via the Higgs exchange

$$\sigma_{\rm SI} = \frac{4}{\pi}\frac{M_1^2 m_p^2}{(M_1+m_p)^2} m_p^2 \left(\frac{\Lambda_q}{m_q}\right)^2 f_p^2,$$

where m_p is the proton mass, $f_p \approx 0.3$ is the scalar form factor, and the effective scalar coupling Λ_q is

$$\Lambda_q = -\frac{y_1^2}{16\pi^2 M_h^2 M_1}\left[\lambda_3 G_1\left(\frac{M_1^2}{M_{\eta\pm}^2}\right) + \frac{\lambda_3+\lambda_4}{2} G_1\left(\frac{M_1^2}{M_{R,I}^2}\right)\right] m_q,$$

$$G_1(x) = \frac{x + (1-x)\log(1-x)}{x}.$$

To make sure the explored parameter space is safe under the tight constraints from direct detection we assume the couplings $\lambda_{3,4} = 0.01$

$\mu \to e\gamma$ bound

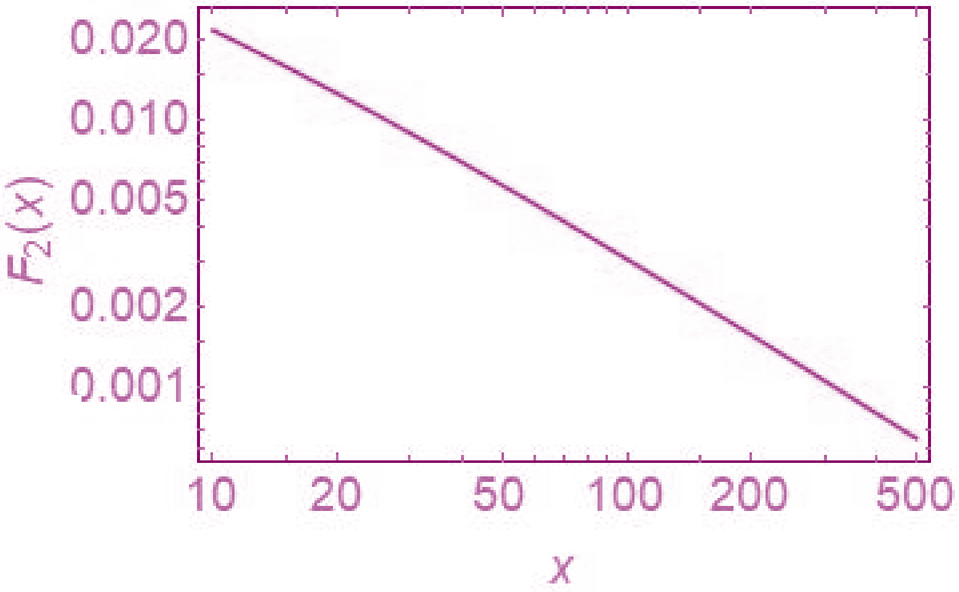
$$\mathrm{BR}(\ell_\alpha \to \ell_\beta \gamma) = \frac{3(4\pi^3)\alpha}{4G_F^2}|A_D|^2 \mathrm{BR}(\ell_\alpha \to \ell_\beta \nu_\alpha \bar{\nu}_\beta),$$

with the dipole form factor

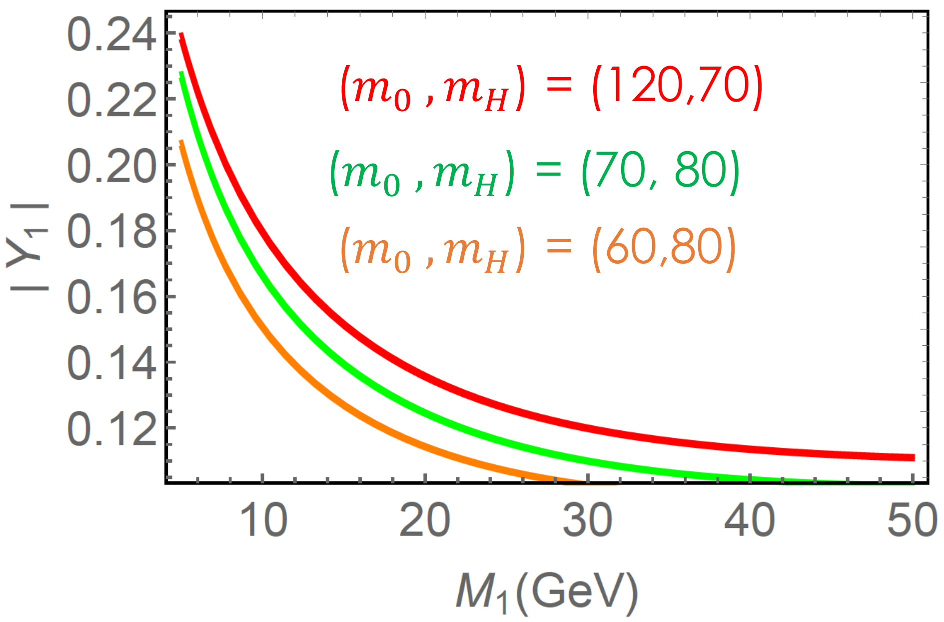
$$A_D = \sum_{i=1}^{3} \frac{y_{i\beta}^* y_{i\alpha}}{2(4\pi)^2 M_{\eta^\pm}^2} F_2(\xi_i)\,.$$

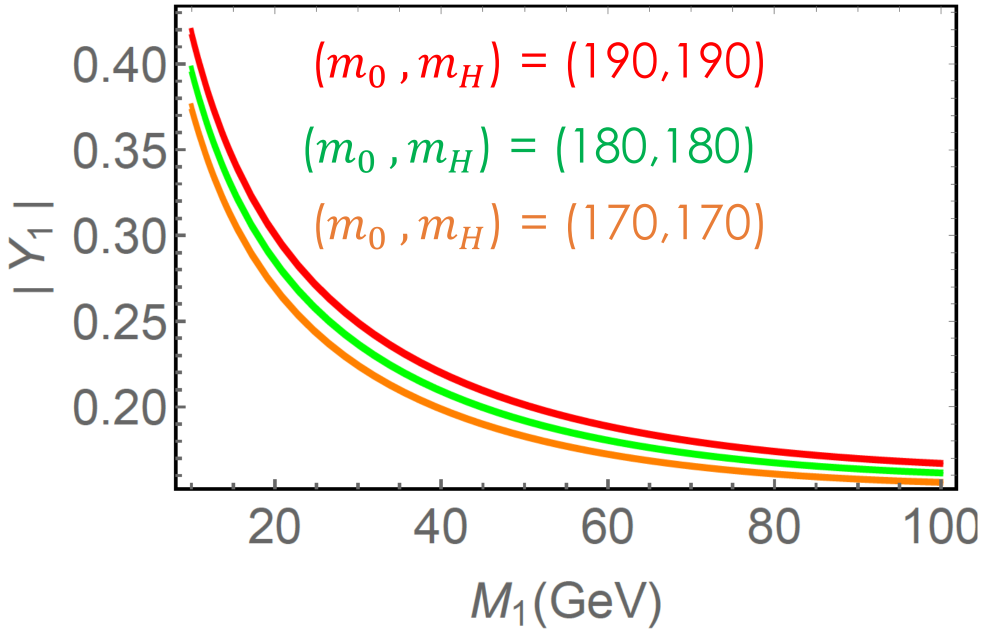
Here $\xi_i = M_i^2/M_{\eta^+}^2$, and the loop function $F_2(x)$ is given by

$$F_2(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \log x}{6(1-x)^4}.$$



$$\Omega_{\rm DM}h^2 = 0.120 \pm 0.001$$



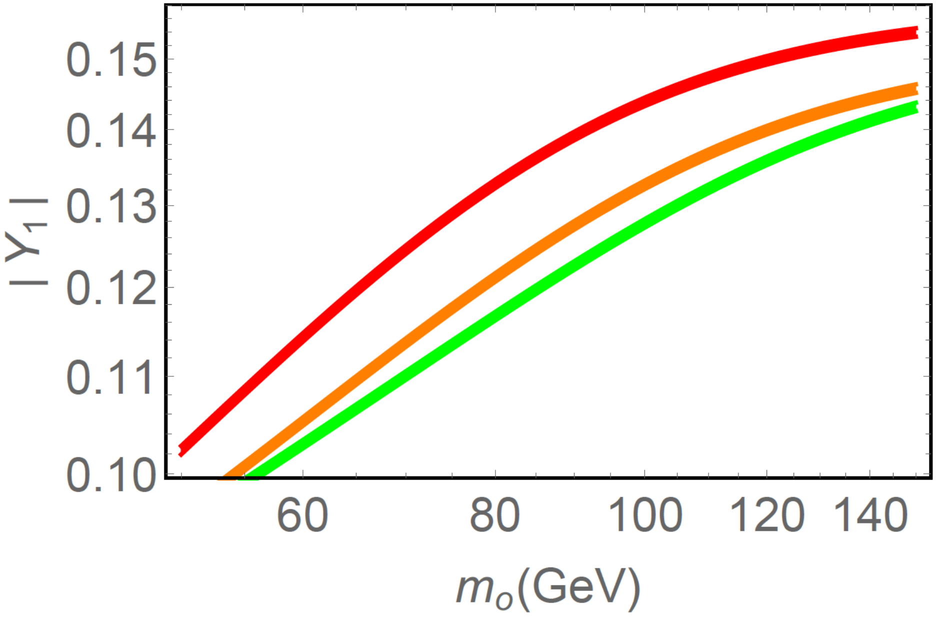


$(M_1, m_o) = (30{,}100)$

$(M_1, m_H) = (20{,}80)$

$(M_1, m_H) = (40, 100)$

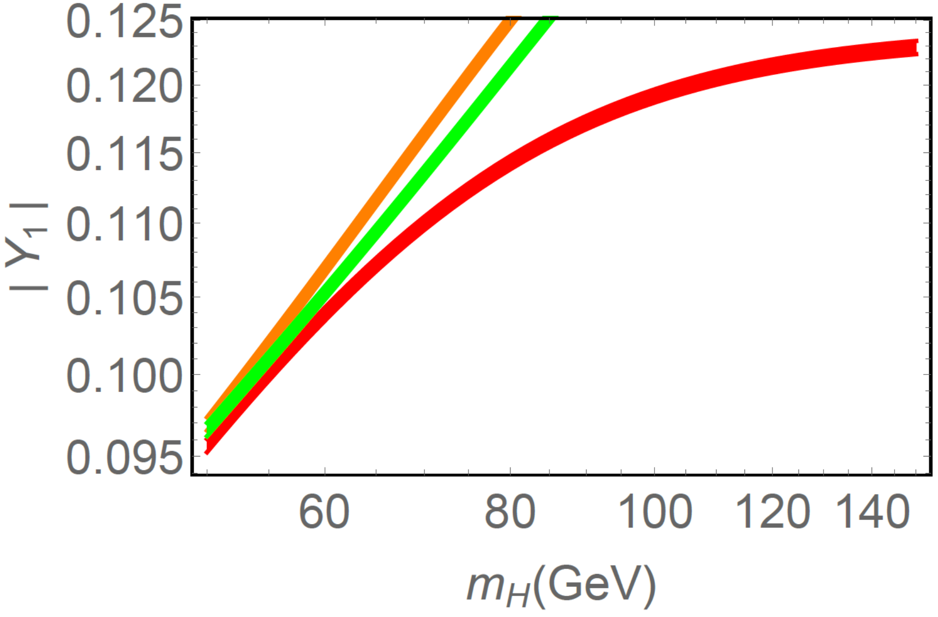
$(M_1, m_H) = (30{,}90)$

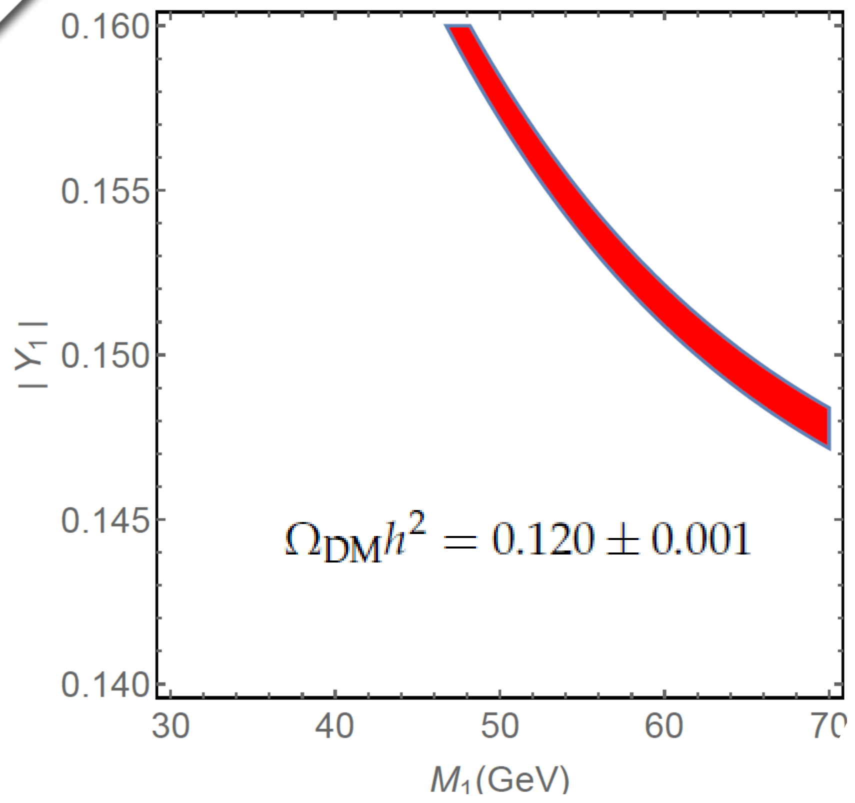


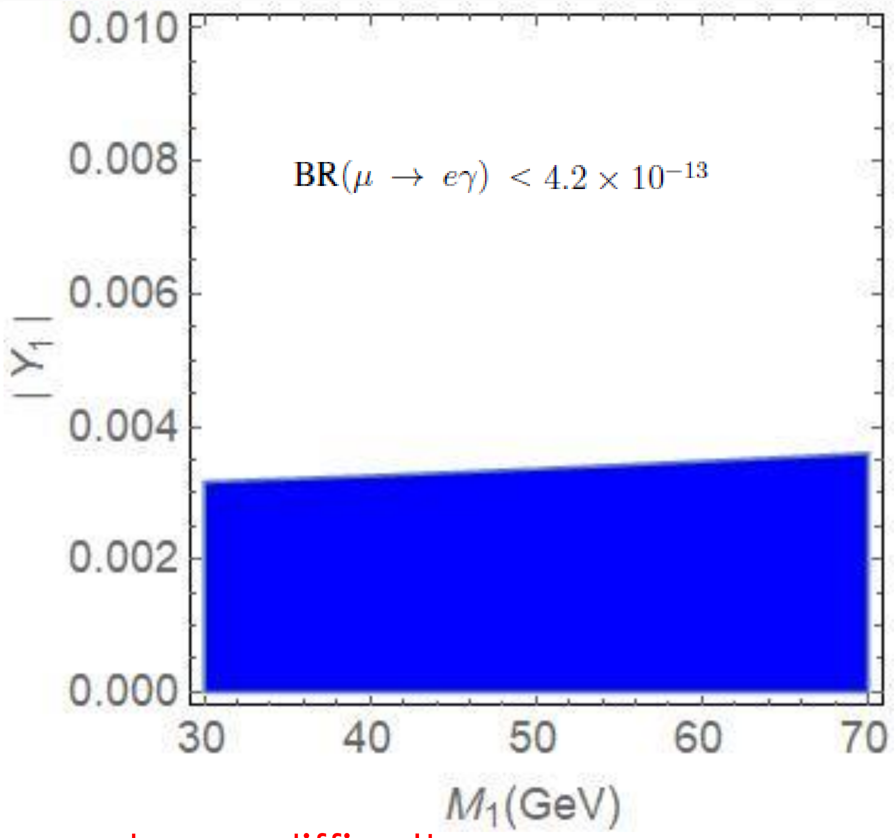
$(M_1, m_o) = (20{,}60)$

$(M_1, m_o) = (40, 120)$

$(M_1, m_o) = (30{,}100)$







Satisfying both constraints at the same time may be so difficult for cold dark matter scenario.

For fermion dark matter N_1, a hierarchical Yukawa structure $|y_{1e}| \ll |y_{1\mu}| \sim |y_{1\tau}| \sim \mathcal{O}(1)$ is usually favored to satisfy constraints from lepton flavor violation and relic density.

arXiv:2207.07382v1 [hep-ph]

	M_1	M_2	M_3	$M_{\eta^\pm}$	$\lvert y_{1e}\rvert$	$\lvert y_{1\mu}\rvert$	$\lvert y_{1\tau}\rvert$	Ωh^2
BP-1	648.7	5.06×10^3	3.39×10^4	1141	2.62×10^{-2}	1.17	1.49	0.122
BP-2	1579	1.82×10^4	1.22×10^5	2647	9.05×10^{-4}	1.99	2.08	0.123
BP-3	2521	6.30×10^4	5.52×10^5	4371	2.17×10^{-2}	2.31	2.95	0.121

Table 1. Benchmark points for MuC studies. Here, all the messes are in the unit of GeV.

Scenario 2: Two Nearly Degenerate Right-handed Fermions

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Exploring X-ray lines as scotogenic signals

Gaber Faisel [a,b], Shu-Yu Ho [a], Jusak Tandean [a,*]

Status Of Three-neutrino Oscillation Parameters, Circa 2013

F. Capozzi, G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, and A. Palazzo

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$$\sin^2\theta_{12} = 0.308 \pm 0.017, \qquad \sin^2\theta_{23} = 0.437^{+0.033}_{-0.023},$$
$$\sin^2\theta_{13} = 0.0234^{+0.0020}_{-0.0019}, \qquad \delta/\pi = 1.39^{+0.38}_{-0.27},$$
$$\delta m^2 = m_2^2 - m_1^2 = (7.54^{+0.26}_{-0.22}) \times 10^{-5}\ \mathrm{eV}^2,$$
$$\Delta m^2 = m_3^2 - \frac{1}{2}(m_1^2 + m_2^2) = (2.43^{+0.06}_{-0.06}) \times 10^{-3}\ \mathrm{eV}^2.$$

$$30.0 < \frac{\Delta m^2}{\delta m^2} < 34.3$$

Table 1
Sample values of the mass parameters $m_{0,H}$, $M_1 \simeq M_2$, and M_3 and Yukawa constants $Y_{1,2,3}$ satisfying the constraints discussed in Section 3.

Set	$\frac{m_0}{\text{GeV}}$	$\frac{m_H}{\text{GeV}}$	$\frac{M_1}{\text{GeV}}$	$\frac{M_3}{\text{GeV}}$	Y_1	Y_2	Y_3
I	340	395	180	235	$0.215 + 0.028i$	$0.281 + 0.036i$	0.419
II	420	440	318	415	$0.215 + 0.027i$	$0.281 + 0.035i$	0.431
III	605	600	350	470	$0.120 + 0.244i$	$0.157 + 0.319i$	0.535
IV	1030	1100	600	805	$-0.360 + 0.041i$	$-0.471 + 0.053i$	0.716
V	1100	1200	600	795	$-0.377 + 0.072i$	$-0.493 + 0.093i$	0.750

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2020 global reassessment of the neutrino oscillation picture

parameter	best fit $\pm$ 1σ	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\theta_{12}/^\circ$	34.3 ± 1.0	32.3–36.4	31.4–37.4
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\theta_{23}/^\circ$ (NO)	49.26 ± 0.79	47.37–50.71	41.20–51.33
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\theta_{23}/^\circ$ (IO)	$49.46^{+0.60}_{-0.97}$	47.35–50.67	41.16–51.25
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\theta_{13}/^\circ$ (NO)	$8.53^{+0.13}_{-0.12}$	8.27–8.79	8.13–8.92
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
$\theta_{13}/^\circ$ (IO)	$8.58^{+0.12}_{-0.14}$	8.30–8.83	8.17–8.96
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
$\delta/^\circ$ (NO)	194^{+24}_{-22}	152–255	128–359
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96
$\delta/^\circ$ (IO)	284^{+26}_{-28}	226–332	200–353

* Using the results of the 2020 global fit, we found that the given set of benchmarks listed in table 1 does not satisfy the constraints from

$\mathcal{B}(\mu \to e\gamma)_{\text{exp}}$ and $\dfrac{\Delta m^2}{\delta m^2}$

for the Dark matter and new scalar masses considered in that scenario.

* Possibility to find viable parameter space still possible for large Dark matter and new scalar masses. However, this turns to not be interesting phenomenologically.


THANK YOU!