Multi-Component Dark Matter from Minimal Flavor Violation

Based on Arxiv[2408.16812]

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Dark Tool @ Torino, 17 June 2025

Outline

Motivation: Why Flavor and Dark Matter

Flavor Violation

- The flavor symmetry of SM:
  $SU(3)^5 = SU(3)_{q_L} \times SU(3)_{u_R} \times SU(3)_{d_R} \times SU(3)_{l_L} \times SU(3)_{e_R}$,
  broken only by Yukawa couplings.

$$\mathcal{L}_{\text{yuk}} = -\bar{q}_L Y_u \tilde{H} u_R - \bar{q}_L Y_d H d_R - \bar{\ell}_L Y_e H e_R + h.c.$$

- **Minimal Flavor Violation (MFV)**: new physics respects SM flavor structure. In MFV, quark Yukawa matrices are treated as spurions transforming as

$$Y_u \sim (3, \bar{3}, 1),\ \ Y_d \sim (3, 1, \bar{3})\ \ \text{under}\ \ \mathcal{G}_F = \mathrm{SU}(3)_{q_L} \times \mathrm{SU}(3)_{u_R} \times \mathrm{SU}(3)_{d_R}$$

  For a new flavor-violating interaction like

$$\mathcal{L} = C_{ij}(\bar{u}_{Ri}\gamma^\mu u_{Rj})O_{\alpha\beta}$$

  MFV requires that the coupling C_{ij} take the form,

$$C_{ij} = c_0\delta_{ij} + \epsilon c_1(Y_u^\dagger Y_u)_{ij} + \epsilon^2 \left[c_2(Y_u^\dagger Y_u Y_u^\dagger Y_u)_{ij} + c_2'(Y_u^\dagger Y_d Y_d^\dagger Y_u)_{ij}\right] + \ldots$$

Stability of flavored DM

Flavored DM candidate:

- Consider a colorless but flavored field:

$$\chi \sim (n_{q_L},\ m_{q_L}) \times (n_{u_R},\ m_{u_R}) \times (n_{d_R},\ m_{d_R})$$

(n_i, m_i) count the number of $(\mathbf{3}_i, \bar{\mathbf{3}}_i)$ representations under $SU(3)_i$

- General decay vertices of χ into SM:

$$O_{\text{decay}} = \chi \times \underbrace{q_L \ldots}_{A} \underbrace{\bar{q}_L \ldots}_{\bar{A}} \underbrace{u_R \ldots}_{B} \underbrace{\bar{u}_R \ldots}_{\bar{B}} \underbrace{d_R \ldots}_{C} \underbrace{\bar{d}_R \ldots}_{\bar{C}} \underbrace{Y_u \ldots}_{D} \underbrace{Y_u^\dagger \ldots}_{\bar{D}} \underbrace{Y_d \ldots}_{E} \underbrace{Y_d^\dagger \ldots}_{\bar{E}} + O_{\text{weak}}$$

A and $\bar{A}$ denote the number of q and $\bar{q}$ fields

Stability of flavored DM:

- Allowing $\mathcal{O}_{\text{decay}}$ requires:

$$SU(3)_c : (A - \bar{A} + B - \bar{B} + C - \bar{C}) \bmod 3 = 0,$$
$$SU(3)_{q_L} : (n_{q_L} - m_{q_L} + A - \bar{A} + D - \bar{D} + E - \bar{E}) \bmod 3 = 0,$$
$$SU(3)_{u_R} : (n_{u_R} - m_{u_R} + B - \bar{B} - D + \bar{D}) \bmod 3 = 0,$$
$$SU(3)_{d_R} : (n_{d_R} - m_{d_R} + C - \bar{C} - E + \bar{E}) \bmod 3 = 0,$$

So for χ to be unstable is $(n - m)$ mod 3=0, where $n = n_{q_L} + n_{u_R} + n_{d_R}$ and $m = m_{q_L} + m_{u_R} + m_{d_R}$. Also it follows that the $\mathcal{O}_{\text{decay}}$ is forbidden and χ is stable if

$$(n_{-}m_{)} \bmod 3 \neq 0$$

Flavored Representations and Stability

(n,m)	$SU(3)_Q \times SU(3)_{u_R} \times SU(3)_{d_R}$	Stable?
$(0,0)$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	
$(1,0)$	$(\mathbf{3},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{3},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{3})$	Yes
$(0,1)$	$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\overline{\mathbf{3}},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\overline{\mathbf{3}})$	Yes
$(2,0)$	$(\mathbf{6},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{6},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{6})$ $(\mathbf{3},\mathbf{3},\mathbf{1})$, $(\mathbf{3},\mathbf{1},\mathbf{3})$, $(\mathbf{1},\mathbf{3},\mathbf{3})$	Yes
$(0,2)$	$(\overline{\mathbf{6}},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\overline{\mathbf{6}},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\overline{\mathbf{6}})$ $(\overline{\mathbf{3}},\overline{\mathbf{3}},\mathbf{1})$, $(\overline{\mathbf{3}},\mathbf{1},\overline{\mathbf{3}})$, $(\mathbf{1},\overline{\mathbf{3}},\overline{\mathbf{3}})$	Yes
$(1,1)$	$(\mathbf{8},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{8},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{8})$ $(\mathbf{3},\overline{\mathbf{3}},\mathbf{1})$, $(\mathbf{3},\mathbf{1},\overline{\mathbf{3}})$, $(\mathbf{1},\mathbf{3},\overline{\mathbf{3}})$ $(\overline{\mathbf{3}},\mathbf{3},\mathbf{1})$, $(\overline{\mathbf{3}},\mathbf{1},\mathbf{3})$, $(\mathbf{1},\overline{\mathbf{3}},\mathbf{3})$	

Source: Adapted from [arXiv:1105.1781v2]

Key Points:

- Representations are assigned under flavor group: $SU(3)_Q \times SU(3)_{u_R} \times SU(3)_{d_R}$
- Stability depends on triality: $(n-m) \bmod 3 \neq 0$
- Our model: red-highlighted entry is a flavor triplet under $SU(3)_{u_R}$

Model Setup: Falvored Dark Matter

A Flavored Scalar as Dark Matter

- Introduce scalar field $S_i \sim (1,3,1)$ under $SU(3)_{q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$.
- scalar potential allowed by the MFV:

$$\begin{aligned} V(H,S) =& m_S^2 S_i^* \left(a_0 \delta_{ij} + \epsilon a_1 (Y_u^\dagger Y_u)_{ij} + \ldots \right) S_j \\ & + \lambda S_i^* \left(b_0 \delta_{ij} + \epsilon b_1 (Y_u^\dagger Y_u)_{ij} + \ldots \right) S_j (H^\dagger H) \\ & + \left(\lambda_0 \delta_{ij} \delta_{kl} + \epsilon \lambda_1 \delta_{ij} (Y_u^\dagger Y_u)_{kl} + \ldots \right) S_i^* S_j S_k^* S_l \end{aligned}$$

with $(Y_u)_{ij} = (V^\dagger \hat{Y}_u)_{ij}$ and $(\hat{Y}_u)_{ij} = y_u^i \delta_{ij}$.

$\Rightarrow$ mass splitting: $\quad M_j^2 - M_i^2 = \epsilon \left(a_1 m_S^2 + b_1 \frac{\lambda v^2}{2} \right) \left\{ (y_u^j)^2 - (y_u^i)^2 \right\}$

Dimension-6 operators

- Five classes of dim-6 operators involving quarks and the scalar field S_i

$$\mathcal{L}_{d=6} = \frac{1}{\Lambda^2}\sum_I c^I_{ijkl}\mathcal{O}^I_{ijkl}$$

$$\mathcal{O}^1_{ijkl} = (\bar{q}_{Li}\gamma^\mu q_{Lj})(S^*_k i\overleftrightarrow{\partial}_\mu S_l), \quad \mathcal{O}^2_{ijkl} = (\bar{u}_{Ri}\gamma^\mu u_{Rj})(S^*_k i\overleftrightarrow{\partial}_\mu S_l),$$

$$\mathcal{O}^3_{ijkl} = (\bar{d}_{Ri}\gamma^\mu d_{Rj})(S^*_k i\overleftrightarrow{\partial}_\mu S_l), \quad \mathcal{O}^4_{ijkl} = (\bar{q}_{Li}\tilde{H}u_{Rj})(S^*_k S_l)$$

$$\mathcal{O}^5_{ijkl} = (\bar{q}_{Li}Hq_{Lj})(S^*_k S_l),$$

- MFV dictates coefficients c^4_{ijkl} as series expansions in Yukawa spurions

$$c^4_{ijkl} = c_1(Y_u)_{il}\delta_{kj} + c_2(Y_u)_{ij}\delta_{kl}$$
$$+\epsilon\left[c_3(Y_uY_u^\dagger Y_u)_{ij}\delta_{kl} + c_4(Y_uY_u^\dagger Y_u)_{il}\delta_{kj} + c_5(Y_u)_{ij}(Y_u^\dagger Y_u)_{kl} + c_6(Y_u)_{il}(Y_u^\dagger Y_u)_{jl}\right]$$
$$+\mathcal{O}(\epsilon^2)$$

- Focus on the $\mathcal{O}^4$ operator at the order of ϵ^0.

$$\mathcal{L}_{d=6} = \frac{1}{\Lambda^2}\left[c_1\bar{u}_i(m_iP_R + m_jP_L)u_j(S^*_jS_i) + c_2(m_i\bar{u}_iu_i)(S^*_jS_j)\right]$$

Decay of Heavy Components

Decay processes

The decay interaction of the heavy component takes the form:

$$\mathcal{L}_{d=6} = \frac{1}{\Lambda^2}\left[c_1 \bar{u}_i (m_i P_R + m_j P_L) u_j (S_j^* S_i) + c_2 (m_i \bar{u}_i u_i)(S_j^* S_j)\right]$$

Mass splittings arise from MFV:

$$M_j^2 - M_i^2 = \epsilon\left(a_1 m_S^2 + b_1 \frac{\lambda v^2}{2}\right)\left\{(y_u^j)^2 (y_u^i)^2\right\}, \quad \frac{M_3^2 - M_1^2}{M_2^2 - M_1^2} = \frac{y_t^2 - y_u^2}{y_c^2 - y_u^2} \simeq \frac{y_t^2}{y_c^2}$$

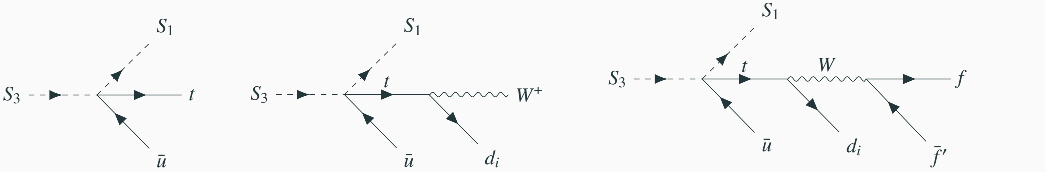
$$\Delta M = M_3 - M_1, \quad \delta M = M_2 - M_1$$

Mass spectrum :

$$normal: \; M_1 < M_2 < M_3, \qquad inverted: \; M_3 < M_2 < M_1$$

Decay processes

- For a normal mass hierarchy ($M_1 < M_2 < M_3$), the heaviest state S_3 can decay through the following channels depending on ΔM:

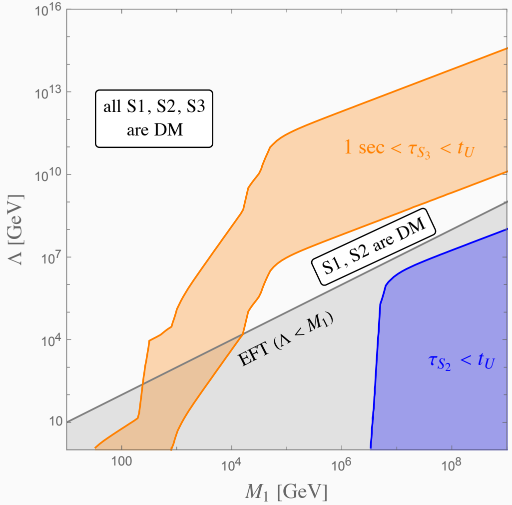


(a) $\Delta M \gtrsim m_t$ (b) $m_W + m_d^i \lesssim \Delta M \lesssim m_t$ (c) $m_u + m_d^i + m_f + m_f' \lesssim \Delta M \lesssim m_W + m_d^i$

Decay widths: (a) $\sim \frac{m_t^2(\Delta M)^5}{480\pi^3\Lambda^4 M_3^2}$ $\quad (b) \sim \frac{(\Delta M)^{11}|V_{ti}|^2}{41472\pi^5\Lambda^4 M_3^2 m_t^2 v^2}$ $\quad (c) \sim \frac{(\Delta M)^{13}|V_{ti}|^2}{11612160\pi^7\Lambda^4 M_3^2 m_t^2 v^4}$

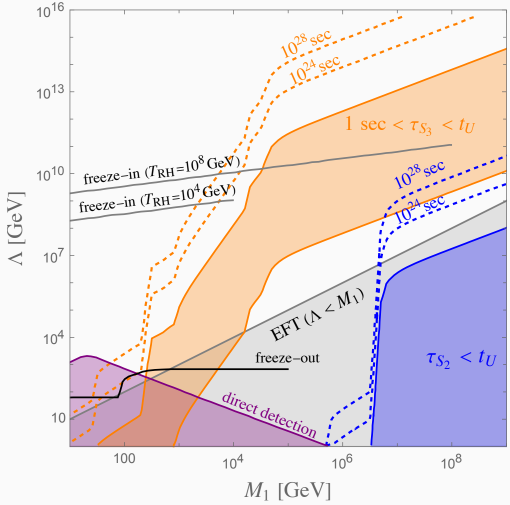
Parameter Space and Phenomenology

Parameter Space and DM Regions



- The model is mainly defined by four parameters: $M_1,\ \Lambda,\ \lambda,\ \epsilon$
- We take $\epsilon \ll 1$ to justify the MFV expansion: $\epsilon \sim \frac{1}{(4\pi)^2} \sim 10^{-2}$
- $\lambda = 0$
- Mass splittings: $\epsilon \simeq \frac{2\Delta M}{y_t^2 M_1} \simeq \frac{2\delta M}{y_c^2 M_1}$
- $\tau_{S_i} > \tau_U \longrightarrow$ DM
- $\tau_{S_i} < \tau_U \longrightarrow$ not DM and have to decay

Experiment constraints



- Direct detection (purple region)
- Relic abundance from freeze-out and freeze-in (black line)
- Indirect detection (dotted lines)

Summary

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Summary:

- We investigated a possibility that, under the MFV framework, the heavy components of such a new flavored field are also stable over cosmological timescales and constitude a significant portion of DM.
- We studied parameter sapce where two or three component of the flavored scalar field have sufficient longevity to serve as DM.

Acknowledgements

Thank you for your attention!