Lepton-Flavored Dark Matter with Minimal Flavor Violation

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CJ Lee & JT, arXiv:1410.6803

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Outline

- Introduction
  - minimal flavor violation
- Lepton-flavored scalar DM with MFV
- Constraints
- Implications for flavor-violating Higgs decay
- Conclusions

Minimal flavor violation

- The standard model (SM) has been successful in describing data on flavor-changing neutral currents and *CP* violaton in the quark sector.
- This motivates the formulation of the principle of minimal flavor violation for quarks: Yukawa couplings are the only sources for the breaking of flavor and *CP* symmetries.

Chivukula & Georgi
Hall & Randall
Buras *et al*.
D'Ambrosio *et al*.

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- It is interesting to extend the MFV principle to the lepton sector
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Cirigliano *et al.*

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- Another major mystery is the identity of the constituents of dark matter.
- It is then also of interest to explore scenarios that address the neutrino and DM puzzles simultaneously.
- We do this with lepton-flavored scalar DM
  - in analogy to quark-flavored DM with MFV.

Batell, Pradler, Spannowsky
Batell, Lin, Wang

Kinetic terms of SM fermions plus three RH neutrinos

- The kinetic Lagrangian of quarks and leptons, including 3 right-handed neutrinos,

$$\mathcal{L}_{\rm k} = i\bar{Q}_{jL}\not{\partial}Q_{jL} + i\bar{U}_{jR}\not{\partial}U_{jR} + i\bar{D}_{jR}\not{\partial}D_{jR} + i\bar{L}_{jL}\not{\partial}L_{jL} + i\bar{\nu}_{jR}\not{\partial}\nu_{jR} + i\bar{E}_{jR}\not{\partial}E_{jR}$$

where $j = 1,2,3$ are summed over, $Q_{jL} = \begin{pmatrix} U_{jL} \\ D_{jL} \end{pmatrix}$, $L_{jL} = \begin{pmatrix} \nu_{jL} \\ \ell_{jL} \end{pmatrix}$

$(U_1, U_2, U_3) = (u, c, t)$, $(D_1, D_2, D_3) = (d, s, b)$, $(E_1, E_2, E_3) = (\ell_1, \ell_2, \ell_3) = (e, \mu, \tau)$

- This is invariant under the global flavor rotations

$$Q_L = \begin{pmatrix} Q_{1L} \\ Q_{2L} \\ Q_{3L} \end{pmatrix} \to \mathcal{V}_Q Q_L\,, \quad U_R = \begin{pmatrix} U_{1R} \\ U_{2R} \\ U_{3R} \end{pmatrix} \to \mathcal{V}_U U_R\,, \quad D_R = \begin{pmatrix} D_{1R} \\ D_{2R} \\ D_{3R} \end{pmatrix} \to \mathcal{V}_D D_R$$

$$L_L = \begin{pmatrix} L_{1L} \\ L_{2L} \\ L_{3L} \end{pmatrix} \to \mathcal{V}_L L_L\,, \quad \nu_R = \begin{pmatrix} \nu_{1R} \\ \nu_{2R} \\ \nu_{3R} \end{pmatrix} \to \mathcal{V}_\nu \nu_R\,, \quad E_R = \begin{pmatrix} E_{1R} \\ E_{2R} \\ E_{3R} \end{pmatrix} \to \mathcal{V}_E E_R$$

where $\mathcal{V}_X \in {\rm U}(3)_X$

- Thus the kinetic terms are symmetric under the global group

$${\rm U}(3)_Q \times {\rm U}(3)_U \times {\rm U}(3)_D \times {\rm U}(3)_L \times {\rm U}(3)_\nu \times {\rm U}(3)_E.$$

Chivukula & Georgi

Mass terms of SM fermions plus three RH neutrinos

★ The Lagrangian responsible for fermion masses

$$\mathcal{L}_{\rm m} = -\bar{Q}_{k,L}\,(Y_u)_{kl}\,U_{l,R}\,\tilde{H} - \bar{Q}_{k,L}\,(Y_d)_{kl}\,D_{l,R}\,H$$
$$-\bar{L}_{k,L}\,(Y_\nu)_{kl}\,\nu_{l,R}\,\tilde{H} - \bar{L}_{k,L}\,(Y_e)_{kl}\,E_{l,R}\,H \;-\; \tfrac{1}{2}\,\overline{\nu^{\rm c}_{k,R}}\,(M_\nu)_{kl}\,\nu_{l,R} \;+\; \text{H.c.}$$

where $k,l = 1,2,3$ are summed over, $Y_{u,d,\nu,e}$ are Yukawa coupling matrices, M_ν is the Majorana mass matrix of the right-handed neutrinos,

and H is the Higgs doublet $\quad H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(h+v) \end{pmatrix}, \quad \tilde{H} = i\sigma_2 H^*$

★ These mass terms explicitly break the global flavor group

$$\mathrm{U}(3)_Q \times \mathrm{U}(3)_U \times \mathrm{U}(3)_D \times \mathrm{U}(3)_L \times \mathrm{U}(3)_\nu \times \mathrm{U}(3)_E .$$

★ The idea of minimal flavor violation presupposes that all flavor- and CP-violating interactions are linked to the known structure of Yukawa couplings. D'Ambrosio *et al.*

★ Accordingly, new effective interactions which violate flavor and CP symmetries must respect the symmetry properties of the Yukawa couplings.

Lepton MFV in SM plus 3 RH neutrinos

- ★ If neutrinos are Dirac fermions, the Majorana mass terms are absent, $M_\nu = 0$.
- ★ Then the MFV hypothesis implies that the lepton Lagrangian is formally invariant under the global group $\mathrm{U}(3)_L \times \mathrm{U}(3)_\nu \times \mathrm{U}(3)_E = G_\ell \times \mathrm{U}(1)_L \times \mathrm{U}(1)_\nu \times \mathrm{U}(1)_E$ where $G_\ell = \mathrm{SU}(3)_L \times \mathrm{SU}(3)_\nu \times \mathrm{SU}(3)_E$.

D'Ambrosio *et al.*, 2002
Cirigliano *et al.*, 2005

- ★ Then $L_{k,L}$, $\nu_{k,R}$, and $E_{k,R}$ transform as fundamental representations of G_ℓ

$$L_L \to V_L L_L\,, \quad \nu_R \to V_\nu \nu_R\,, \quad E_R \to V_E E_R\,, \quad V_{L,\nu,E} \in \mathrm{SU}(3)$$

and the Yukawa couplings are taken to be spurions transforming as

$$Y_\nu \to V_L Y_\nu V_\nu^\dagger\,, \qquad Y_e \to V_L Y_e V_E^\dagger$$

- ★ We work in the basis where Y_e is diagonal, $Y_e = \sqrt{2}\,\mathrm{diag}(m_e, m_\mu, m_\tau)/v$ and $\nu_{k,L}$, $\nu_{k,R}$, $E_{k,L}$, and $E_{k,R}$ refer to the mass eigenstates.

Hence $$L_{k,L} = \begin{pmatrix} (U_{\mathrm{PMNS}})_{kl}\,\nu_{l,L} \\ E_{k,L} \end{pmatrix}, \qquad Y_\nu = \frac{\sqrt{2}}{v} U_{\mathrm{PMNS}}\,\hat{m}_\nu$$

$\hat{m}_\nu = \mathrm{diag}(m_1, m_2, m_3)$ with $m_{1,2,3}$ being the light neutrino eigenmasses.

Lepton MFV with Majorana neutrinos

* If neutrinos are Majorana fermions, generally $M_\nu \neq 0$.

* For $M_\nu \gg M_{\rm D} = vY_\nu/\sqrt{2}$ the seesaw mechanism is activated involving the 6×6 neutrino mass matrix $\mathbf{M} = \begin{pmatrix} 0 & M_{\rm D} \\ M_{\rm D}^{\rm T} & M_\nu \end{pmatrix}$ in the $(U^*_{\rm PMNS}\nu_L^{\rm c}, \nu_R)^{\rm T}$ basis.

* The resulting matrix of light neutrino masses is

$$m_\nu = -\frac{v^2}{2} Y_\nu M_\nu^{-1} Y_\nu^{\rm T} = U_{\rm PMNS}\, \hat{m}_\nu\, U_{\rm PMNS}^{\rm T}$$

now $U_{\rm PMNS}$ containing $P = {\rm diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1)$ multiplied from the right, $\alpha_{1,2}$ being the Majorana phases.

* Thus Y_ν needs to be modified, and one can instead take Y_ν to be

$$Y_\nu = \frac{i\sqrt{2}}{v} U_{\rm PMNS}\, \hat{m}_\nu^{1/2} O M_\nu^{1/2}$$

Casas & Ibarra

where O satisfies $OO^{\rm T} = \mathbb{1}$ and $M_\nu = {\rm diag}(M_1, M_2, M_3)$.

- To have new interactions, one inserts $Y_{\nu,e}^{(\dagger)}$ and their products among SM and new fields to form operators invariant under $G_\ell = \mathrm{SU}(3)_L \times \mathrm{SU}(3)_\nu \times \mathrm{SU}(3)_E$ and singlet under the SM gauge group.
- Of interest here are $\mathsf{A} = Y_\nu Y_\nu^\dagger$ and $\mathsf{B} = Y_e Y_e^\dagger$
- Assuming neutrinos to be Majorana fermions, we take $\nu_{k,R}$ to be degenerate, with $M_\nu = \mathcal{M}\mathbb{1}$, and O real.

  Hence $\mathsf{A} = Y_\nu Y_\nu^\dagger = \frac{2}{v^2}\mathcal{M}\, U_{\mathrm{PMNS}}\,\hat{m}_\nu U_{\mathrm{PMNS}}^\dagger$ with $\hat{m}_\nu = \mathrm{diag}(m_1, m_2, m_3)$

Lepton-flavored scalar triplet

- ⋆ SM-gauge-singlet scalar G_ℓ-triplet $\tilde{s} = \begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \\ \tilde{s}_3 \end{pmatrix} \sim (3,1,1)$

  where $G_\ell = \mathrm{SU}(3)_L \times \mathrm{SU}(3)_\nu \times \mathrm{SU}(3)_E$

- ⋆ For DM stability, invoke a Z_2 symmetry: $\tilde{s} \to -\tilde{s}$

- ⋆ Scalar potential in renormalizable Lagrangian

$$\mathcal{V} = \mu_H^2 H^\dagger H + \tilde{s}^\dagger \mu_s^2 \tilde{s} + \lambda_H (H^\dagger H)^2 + 2\, H^\dagger H\, \tilde{s}^\dagger \Delta_{HS} \tilde{s} + (\tilde{s}^\dagger \Delta_{SS} \tilde{s})^2$$

$$\supset \tilde{s}^\dagger \left(\mu_{s0}^2 \mathbb{1} + \mu_{s1}^2 \mathsf{A} + \mu_{s2}^2 \mathsf{A}^2\right) \tilde{s} \; + \; 2H^\dagger H\, \tilde{s}^\dagger \left(\lambda_{s0} \mathbb{1} + \lambda_{s1} \mathsf{A} + \lambda_{s2} \mathsf{A}^2\right) \tilde{s}$$

  with $\mathsf{A} = Y_\nu Y_\nu^\dagger$ assumed to have elements $\gg$ than those of $\mathsf{B} = Y_e Y_e^\dagger$

  and the Higgs doublet $H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(h+v) \end{pmatrix}$

- ⋆ Since A is Hermitian, $\mathsf{A} = \mathcal{U}\, \mathrm{diag}(\hat{\mathsf{A}}_1, \hat{\mathsf{A}}_2, \hat{\mathsf{A}}_3)\, \mathcal{U}^\dagger$ where $\mathcal{U}$ is a unitary matrix

- ⋆ In terms of mass eigenstates $S = \begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix} = \mathcal{U}^\dagger \tilde{s}$

$$\mathcal{L} \supset -m_{S_k}^2 S_k^* S_k \; - \; \lambda_k (h^2 + 2hv) S_k^* S_k \; - \; (\lambda'_k S_k^* S_k)^2$$

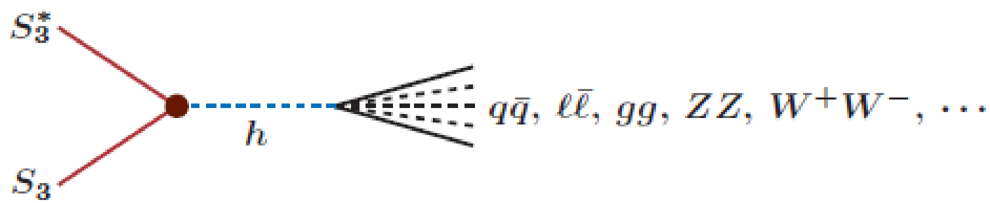
  where $m_{S_k}^2 = \mu_k^2 + \lambda_k v^2, \quad \mu_k^2 = \mu_{s0}^2 + \mu_{s1}^2 \hat{\mathsf{A}}_k + \mu_{s2}^2 \hat{\mathsf{A}}_k^2, \quad \lambda_k = \lambda_{s0} + \lambda_{s1} \hat{\mathsf{A}}_k + \lambda_{s2} \hat{\mathsf{A}}_k^2$

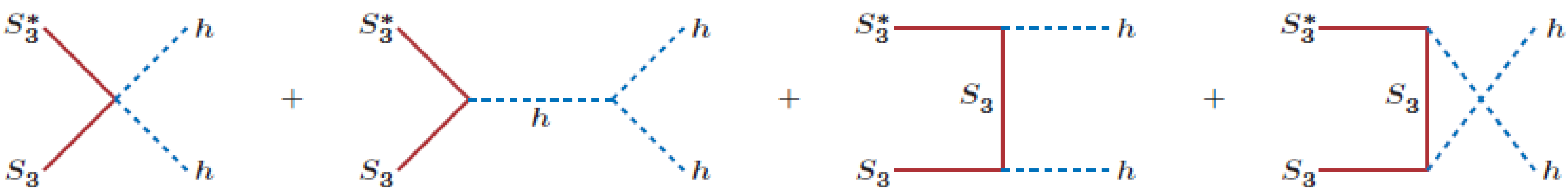
DM relic density & annihilation

★ Relic density $$\Omega\hat{h}^2 = \frac{2.14\times10^9\,x_f/\text{GeV}}{\sqrt{g_*}\,m_{\text{Pl}}\,(\hat{a}+3\hat{b}/x_f)}\,, \qquad x_f = \ln\frac{0.038\,m_{S_3}m_{\text{Pl}}\,(\hat{a}+6\hat{b}/x_f)}{\sqrt{g_*\,x_f}}$$

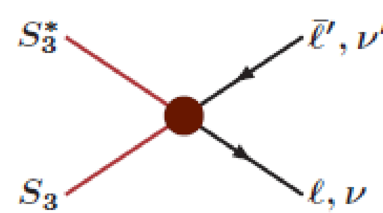
where $\sigma_{\text{ann}}v_{\text{rel}}^2 = \hat{a}+\hat{b}v_{\text{rel}}$ is the rate of $S_3^*S_3$ annihilation into SM particles.

★ Annihilation diagrams with h-$\tilde{s}$ renormalizable couplings



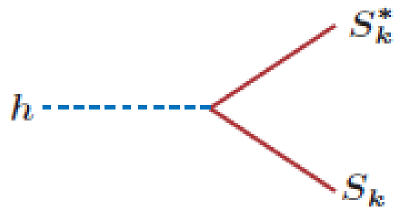


★ Annihilation diagrams with lepton-$\tilde{s}$ effective couplings



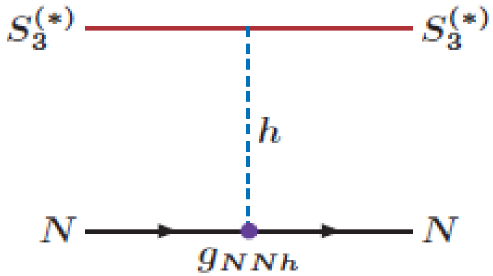
- If $2m_{S_k} < m_h$, the hS_k couplings must satisfy the limit on the branching ratio $\mathcal{B}(h \to \text{invisible/exotic}) < 19\%$ from collider data.

Falkowski, Riva, Urbano
Giardino *et al.*
Belanger *et al.*
Cheung, Lee, Tseng



$$\mathcal{B}(h \to SS) = \frac{\sum_k \Gamma_{h \to S_k^* S_k}}{\Gamma_h^{\rm SM} + \sum_k \Gamma_{h \to S_k^* S_k}} , \quad \Gamma_{h \to S_k^* S_k} = \frac{\lambda_3^2 v^2}{4\pi m_h} \sqrt{1 - \frac{4m_{S_k}^2}{m_h^2}} , \quad m_h = 125.1 \text{ GeV} , \quad \Gamma_h^{\rm SM} = 4.08 \text{ MeV}$$

- DM direct search constraints apply only to the hS_3 coupling, λ_3.



$$\sigma_{\rm el}^N = \frac{\lambda_3^2 \, g_{NNh}^2 \, v^2 \, m_N^2}{\pi \left(m_{S_3} + m_N\right)^2 m_h^4}$$

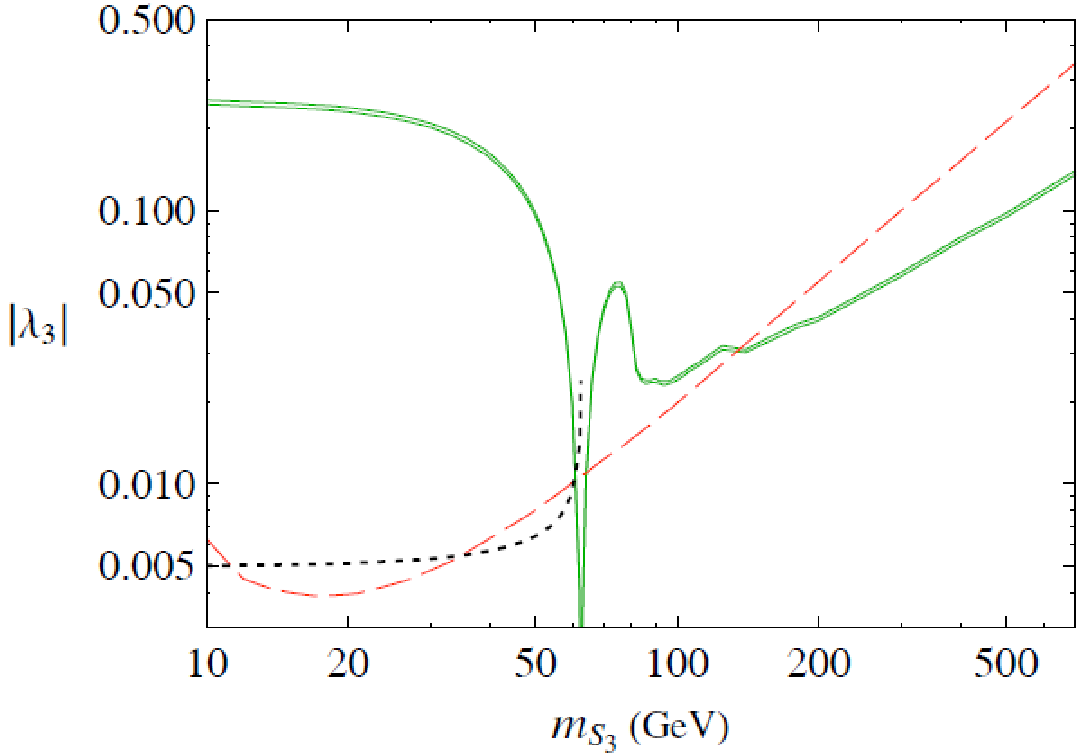
Results for λ_3

- We assume the neutrino mass inverted hierarchy with $m_3 = 0$, require the largest eigenvalue of A to have a size of 1, and pick $\mu_{s0}^2 + \lambda_{s0} v^2 = \mu_{s1}^2 + \lambda_{s1} v^2 = \mu_{s2}^2 + \lambda_{s2} v^2$ for

$$m_{S_k}^2 = \mu_{s0}^2 + \lambda_{s0} v^2 + \frac{2(\mu_{s1}^2 + \lambda_{s1} v^2)\mathcal{M}\, m_k}{v^2} + \frac{4(\mu_{s2}^2 + \lambda_{s2} v^2)\mathcal{M}^2 m_k^2}{v^4}$$

- Values of $|\lambda_3|$ satisfying the relic constraint (green solid curve) compared with upper limits on $|\lambda_3|$ from Higgs invisible/exotic decay data (dotted black curve) and from LUX (red dashed curve).

PDG 2014 $\Omega h^2 = 0.1198 \pm 0.0026$



Hence the λ_3 contribution to the relic density is small for $m_{S_k} < O(100\text{ GeV})$ except near $m_h/2$.

Effective dimension-six lepton-S couplings

- Effective dimension-6 operators satisfying the MFV requirement and coupling SM leptons to $\tilde{s}$

$$\mathcal{L}' = \frac{C^{L}_{bdkl}}{\Lambda^2} O^{L}_{bdkl} + \frac{C^{R}_{bdkl}}{\Lambda^2} O^{R}_{bdkl} + \left(\frac{C^{LR}_{bdkl}}{\Lambda^2} O^{LR}_{bdkl} + \mathrm{H.c.} \right)$$

$b, d, k, l = 1, 2, 3$ are summed over,

$$C^{L}_{bdkl} = (\Delta_{LL})_{bd}(\Delta_{SS})_{kl} + (\Delta_{LS})_{bl}(\Delta_{SL})_{kd} + (\Delta_{LS})_{kd}(\Delta_{SL})_{bl}\,, \quad O^{L}_{bdkl} = i\bar{L}_{b,L}\gamma^{\rho} L_{d,L}\, \tilde{s}^{*}_{k} \overleftrightarrow{\partial}_{\rho} \tilde{s}_{l}$$

$$C^{R}_{bdkl} = \delta_{bd}\,(\Delta'_{SS})_{kl}\,, \quad O^{R}_{bdkl} = i\bar{E}_{b,R}\gamma^{\rho} E_{d,R}\, \tilde{s}^{*}_{k} \overleftrightarrow{\partial}_{\rho} \tilde{s}_{l}$$

$$C^{LR}_{bdkl} = (\Delta_{LY} Y_e)_{bd}(\Delta''_{SS})_{kl} + (\Delta'_{LS})_{bl}(\Delta_{SY} Y_e)_{kd}\,, \quad O^{LR}_{bdkl} = \bar{L}_{b,L} E_{d,R}\, \tilde{s}^{*}_{k} \tilde{s}_{l}\, H$$

The mass scale Λ characterizes the underlying heavy new physics.

- Assume $\Delta = \xi_1 \mathbb{1} + \xi_2 \mathsf{A} + \xi_4 \mathsf{A}^2$

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The mass scale Λ characterizes the underlying heavy new physics.

- Assume $\Delta = \xi_1 \mathbb{1} + \xi_2 \mathsf{A} + \xi_4 \mathsf{A}^2$
- For simplicity, take

$$C^{LR}_{bdkl} = \frac{\sqrt{2}\, \kappa_{LR} m_{\ell_d}}{v} \delta_{bl} \delta_{dk} \,, \qquad C^L_{bdkl} = 2\kappa_L \delta_{bl} \delta_{dk} \,, \qquad C^R_{bdkl} = \kappa_R \delta_{bd} \delta_{kl}$$

Effective couplings satisfying relic data

- The effective dimension-six operators (O^L, O^R, and O^{LR}) contribute to S_3 annihilations into $\ell_1\ell_2$ and (for $O^{L,R}$) $\nu_1\nu_2$ pairs.
- They need to be consistent with the observed relic abundance.

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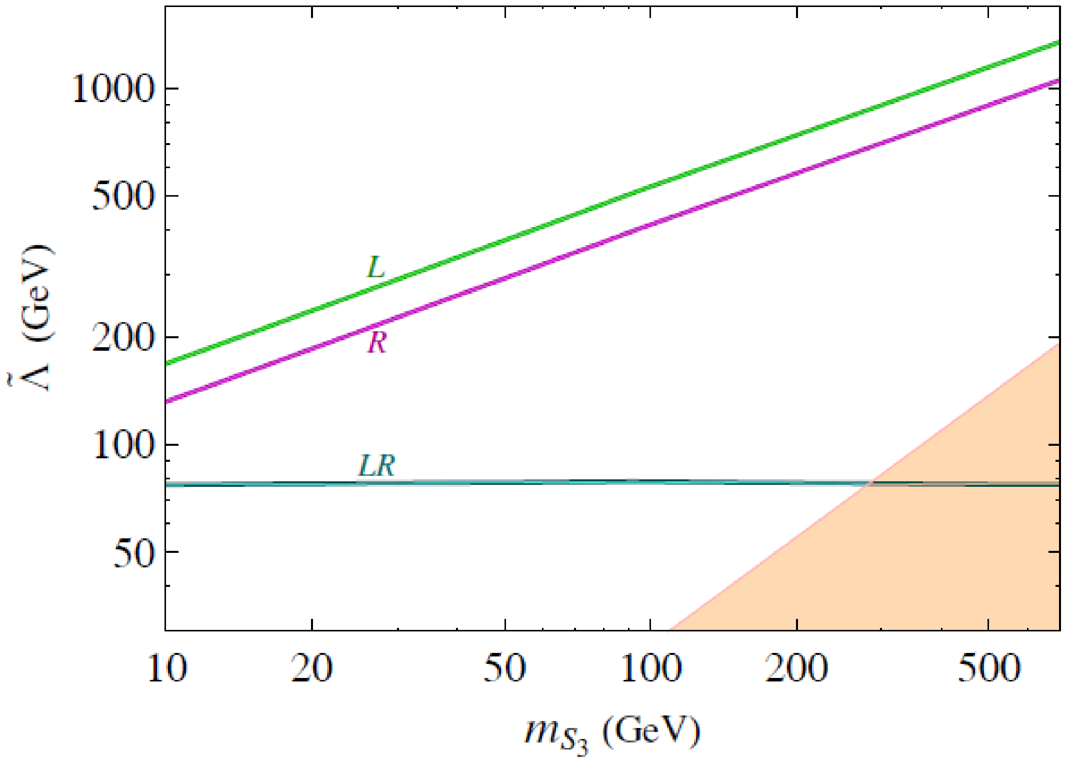
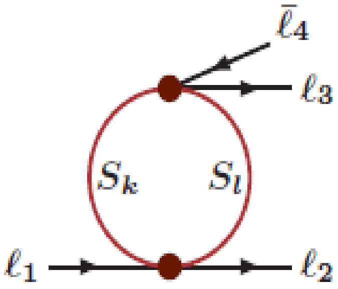


- In the orange region, corresponding to $2\pi\Lambda/|\kappa|^{1/2} < m_{S_2}$, the effective theory description breaks down.

Goodman *et al.*

Constraints from flavor-changing lepton decays

- The effective dimension-six $\ell'\ell S'S$ ouplings can also induce, at one loop, flavor-changing lepton decays $\ell_1 \rightarrow \ell_2\, \ell_3\, \ell_4$



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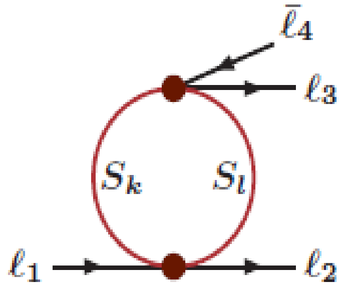

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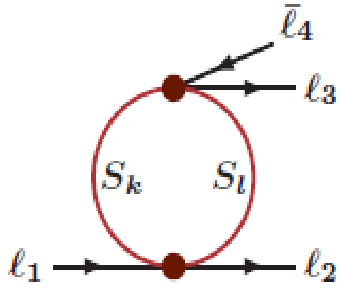
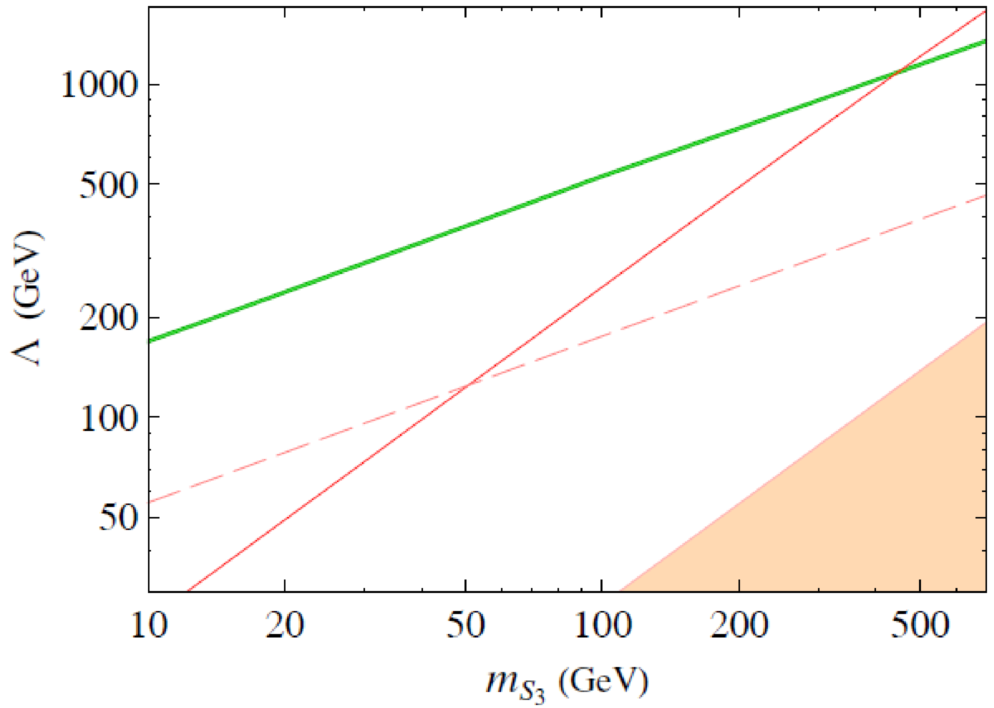


- The κ_{LR} contributions consistent with the relic density data are well above the lower limit inferred from experimental bounds on these decays.
- But the corresponding κ_L contributions are in conflict with the flavor-violating decay data if $m_{S_k} > 500\,\text{GeV}$.
  - The red solid curve indicates the lower limit from $\mathcal{B}(\mu\to 3e)$ data.



Potential implications for $h \to \mu\tau$

- CMS recently observed a slight excess of $h \to \mu\tau$ at 2.5σ
  - If a signal, $\mathcal{B}(h \to \mu\tau) = \left(0.89^{+0.40}_{-0.37}\right)\%$
  - If a statistical fluctuation, $\mathcal{B}(h \to \mu\tau) < 1.57\%$ at 95% CL.
- Other data from ATLAS & CMS, respectively:
  - $h \to \tau\tau$ $\quad \sigma/\sigma_{\rm SM} = 1.42^{+0.44}_{-0.38}$ and 0.91 ± 0.27
  - $\mathcal{B}(h \to \mu\bar{\mu}) < 1.5 \times 10^{-3}$ and 1.6×10^{-3}

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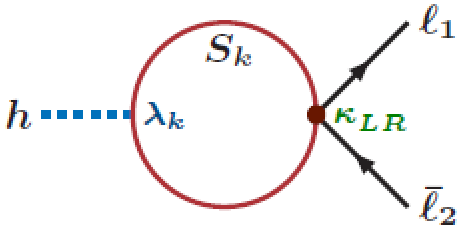

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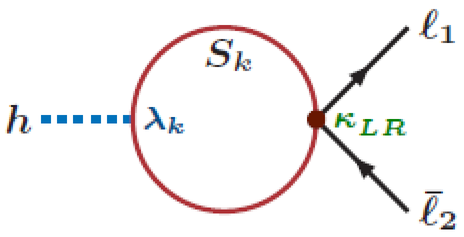

- The S_k contribution yields
  - $0.52\% < \mathcal{B}(h \to \mu\tau) < 0.79\%$ with $-\lambda_{1,2} \sim 2.4 - 7.2$ and $\lambda_3 \sim 0$ if $\kappa_{LR} = 1$ and $(m_{S_k}, \Lambda) \sim (70\text{-}200, 78)$ GeV.
  - $1.6 < \Gamma_{h\to\tau\bar{\tau}}/\Gamma^{\rm SM}_{h\to\tau\bar{\tau}} < 1.8$
  - $\mathcal{B}(\tau \to \mu\gamma)$ over 30 times below its experimental limit.

Conclusions

- We have explored scalar DM that is a member of a lepton flavor triplet within the framework of leptonic minimal flavor violation.
- The theory includes the type-I seesaw mechanism and has a Z_2 symmetry added to stabilize the DM candidate.
- The new scalars couple to SM particles via renormalizable interactions and to leptons through effective dimension-6 operators.
- We considered constraints on the scalars from the Higgs data, observed relic density, DM direct detection experiments, and searches for flavor-violating charged-lepton decays. The allowed parameter space can be probed further with future data.
- The new scalar interactions can roughly account for the CMS tentative hint of $h \to \mu\tau$.