Dark matter direct detection at one loop

Michael A. Schmidt

12 December 2017

CosPA 2017

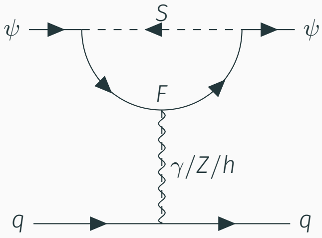
based on
C. Hagedorn, J. Herrero-García, E. Molinaro, MS [1712.xxxxx]
J. Herrero-García, E. Molinaro, MS [1712.xxxxx]

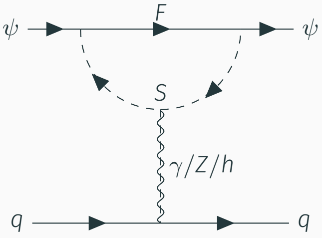
THE UNIVERSITY OF SYDNEY

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Motivation

- No clear evidence for DM in direct/indirect detection or at LHC
- Only hints from DAM.*
- Option: DM is not directly coupled to quarks
- Examples: fermionic singlet DM ψ such as bino, fermionic DM in scotogenic model, or models explaining the DAMPE result
- Direct detection occurs at one loop
- Next generation (liquid noble gas) experiments could probe it



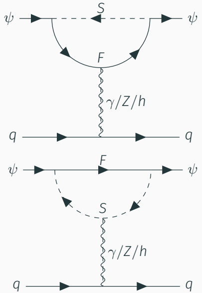


Simplified fermionic DM model

Dark sector	Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{dm}$
Dark matter	ψ	1	1	0	1
Dark scalar	S	1	d_F	Y_F	q_s
Dark fermion	F	1	d_F	Y_F	$q_s + 1$

$$\mathcal{L}_\psi = i\,\overline{\psi}\,\partial\!\!\!/\,\psi - m_\psi\,\overline{\psi}\,\psi + i\,\overline{F}\,D\!\!\!\!/\,F - m_F\,\overline{F}\,F + (D_\mu S)^\dagger D^\mu S$$
$$- \left(y_1\,\overline{F_R}\,S\,\psi_L + y_2\,\overline{F_L}\,S\,\psi_R + \text{H.c.}\right) - \lambda_{HS}\,v\,h\,S^\dagger S + \ldots$$

- Higgs portal coupling may arise in different ways
- Easy to generalise to larger dark symmetry groups



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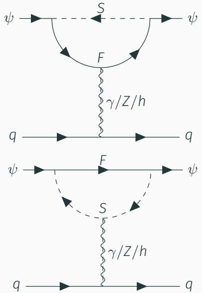

SM fields in loop

1. $F \to L_L/e_R$: ψ or S have $L = 1$ LFV, EDM/AMMs, LNV
2. $F \to \nu_R$: ν_R and ψ or S have $L = 1$ Gonzalez-Macias, Escudero, ...
3. $S \to H$: mixing $\psi - F_0$, thus tree-level H/Z exchange

(Relevant) effective operators for direct detection

Dirac DM

- Electric and magnetic dipoles: $\mathcal{L} = \mu_\psi \mathcal{O}_{\rm mag} + d_\psi \mathcal{O}_{\rm edm}$ [long-range]

$$\mathcal{O}_{\rm mag} = \frac{e}{8\pi^2}(\overline{\psi}\sigma^{\mu\nu}\psi)F_{\mu\nu}, \qquad \mathcal{O}_{\rm edm} = \frac{e}{8\pi^2}(\overline{\psi}\sigma^{\mu\nu}i\gamma_5\psi)F_{\mu\nu}\,,$$

- Vector operators induced by Z/γ-penguins [anapole $(\overline{\psi}\gamma^\mu\psi)(\partial^\nu F_{\mu\nu}) \equiv \mathcal{O}^V_{\rm SI}$ by EOM]

$$\mathcal{O}^V_{\rm SI} = (\overline{\psi}\gamma^\mu\psi)(\overline{q}\gamma_\mu q) \qquad \mathcal{O}^{AV}_{\rm SD} = (\overline{\psi}\gamma^\mu\gamma_5\psi)(\overline{q}\gamma_\mu\gamma_5 q),$$

- Scalar operators [and gluon operator induced by heavy quarks]

$$\mathcal{O}^S_{\rm SI} = m_q(\overline{\psi}\psi)(\overline{q}q) \qquad \mathcal{O}^G_{\rm SI} = \frac{\alpha_s}{8\pi}(\overline{\psi}\psi)G^{a\mu\nu}G^a_{\mu\nu}$$

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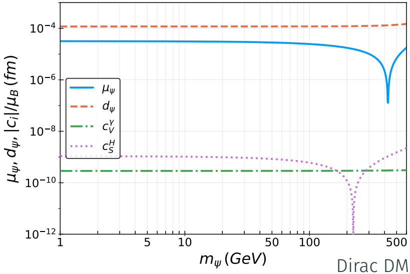
Majorana DM

- no dipole and vector operators
- P-violating vector-operator [momentum suppressed]

$$\mathcal{O}^{AV}_V = (\overline{\psi}\gamma^\mu\gamma_5\psi)\,(\overline{q}\gamma_\mu q)$$



For Dirac DM ψ $[m_\psi \ll m_F < m_S]$

$$\mu_\psi \approx -\frac{Q_F}{4\,m_S}\left(|y_V|^2 - |y_A|^2\right) x_F\, \frac{1 - x_F^2 + 2\,\ln x_F}{(1 - x_F^2)^2}$$

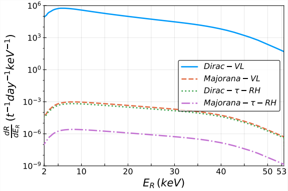
$$d_\psi \approx -\frac{Q_F}{2\,m_S}\,\mathrm{Im}[y_V^*\,y_A]\, x_F\, \frac{1 - x_F^2 + 2\,\ln x_F}{(1 - x_F^2)^2}$$

where

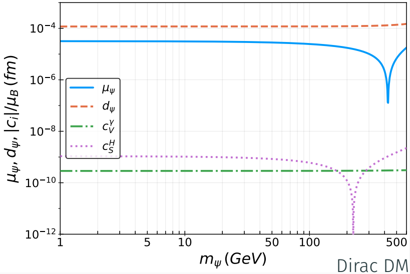
$$x_F \equiv \frac{m_F}{m_S} \qquad \text{and} \qquad y_{V,A} = \frac{y_2 \pm y_1}{2}\,.$$

Dominant contribution:

- Dirac DM: magnetic and electric dipole moments
- Majorana DM: Higgs, but also photon penguin.



Dominant interactions: electric/magnetic dipole moments



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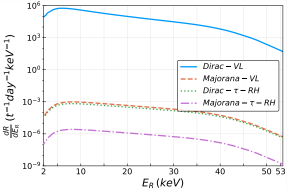
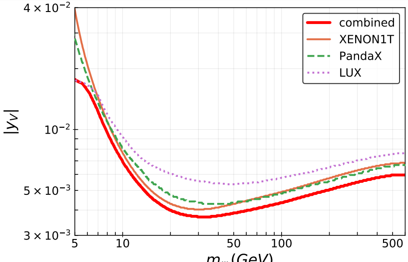
All contributions have to be considered simultaneously



- Analytical expressions valid for general models provided in paper and compared to existing results Berlin, Chang, Agrawal, Kumar, Schmidt, Kopp, Ibarra...
- Implemented with DirectDM 1708.02678 and LikeDM 1708.04630

Direct detection limits

Vector-like fermions



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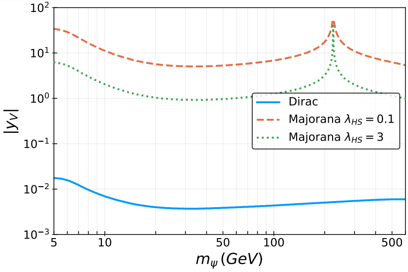

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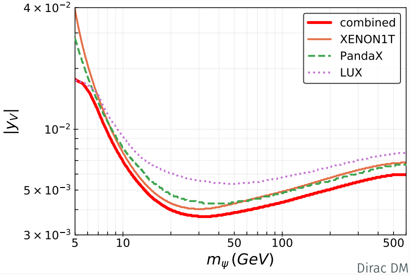
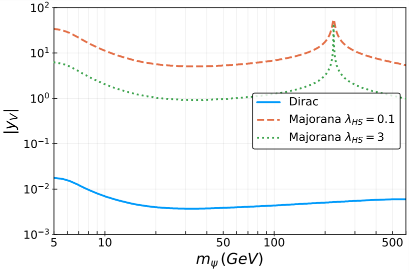
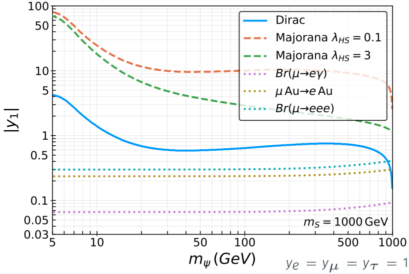
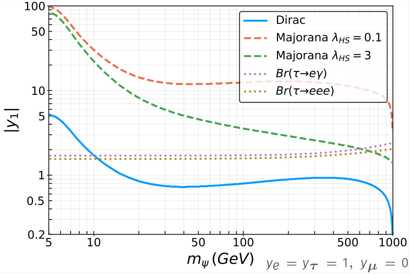




Right-handed charged leptons





Connection to neutrino masses: scotogenic model with Dirac fermion

Scotogenic model with Dirac DM

Simple example of loopy DD with radiative ν masses:

Dirac DM ψ, $F \equiv L_L$, $S = \Phi, \Phi'$. Dark global (anomaly-free) $U(1)_{\rm DM}$

Field	$SU(3)_{\rm C}$	$SU(2)_{\rm L}$	$U(1)_{\rm Y}$	$U(1)_{\rm DM}$
Φ	1	2	1/2	1
Φ'	1	2	-1/2	1
ψ	1	1	0	1

Just **one fermionic singlet** ψ needed. $\mathbf{y}_{\Phi^{(\prime)}}$ are 3-component vectors

$$\mathcal{L}_\psi \supset i\,\overline{\psi}\,\partial\!\!\!/\,\psi - m_\psi\,\overline{\psi}\,\psi - \left(y^\alpha_\Phi\,\overline{\psi}\,\tilde{\Phi}^\dagger L^\alpha_L + (y^\alpha_{\Phi'})^*\,\overline{\psi}\,\tilde{\Phi}'^\dagger \tilde{L}^\alpha_L + \text{H.c.}\right).$$

Two neutral scalars $\eta_0^{(\prime)}$ (mixing angle θ),
two charged scalars $\eta^{(\prime)\pm}$ (no mixing)

$$V \supset \lambda_{H\Phi\Phi'}\left[(H^\dagger\tilde{\Phi}')(H^\dagger\Phi) + \text{H.c.}\right] \quad\longrightarrow\quad \sin 2\theta \propto \lambda_{H\Phi\Phi'}\,.$$

Different classifications

Introduction

Discussion

Survey of models

Y. Cai, J. Herrero-Garcia, MS, A. Vicente, R. Volkas [1706.08524]

frontiers in Physics

REVIEW
published: 04 December 2017
doi: 10.3389/fphy.2017.00063

Check for updates

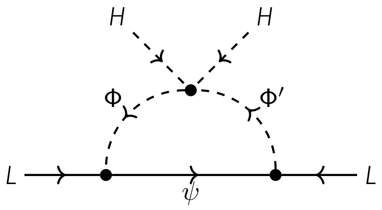
From the Trees to the Forest: A Review of Radiative Neutrino Mass Models

Yi Cai[1,2], Juan Herrero García[3*], Michael A. Schmidt[4*], Avelino Vicente[5] and Raymond R. Volkas[2]

[1] School of Physics, Sun Yat-sen University, Guangzhou, China, [2] ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, The University of Melbourne, Melbourne, VIC, Australia, [3] ARC Centre of Excellence for Particle Physics at the Terascale, Department of Physics, The University of Adelaide, Adelaide, SA, Australia, [4] ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, The University of Sydney, Sydney, NSW, Australia, [5] Instituto de Física Corpuscular (CSIC-Universitat de València), Valencia, Spain

A plausible explanation for the lightness of neutrino masses is that neutri… at tree level, with their mass (typically Majorana) being generated r… …re loops. The new couplings, together with the suppression… …, imply that the new degrees of freedom cannot be to… …V scale). Therefore, in these models there are n… …tested using different searches, making… …ealing. In particular, the new partic… …uce signals in lepton-flavor an… …neutrinos), which are n… …mixings. The mai… …space fro…

Majorana ν mass



$$\mathcal{M}_\nu^{\alpha\beta} = \frac{\sin 2\theta\, m_\psi}{32\,\pi^2}\left(y_\Phi^\alpha\, y_{\Phi'}^\beta + y_{\Phi'}^\alpha y_\Phi^\beta\right)\left[\frac{m_{\eta_0}^2}{m_{\eta_0}^2 - m_\psi^2}\log\frac{m_{\eta_0}^2}{m_\psi^2} - (\eta_0 \leftrightarrow \eta_0')\right]$$

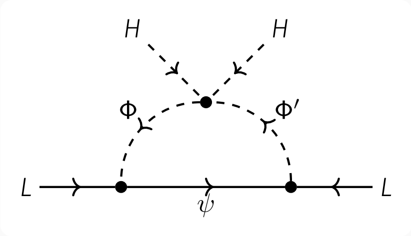
Lepton number L violated by combination of $\mathbf{y}_\Phi$, $\mathbf{y}'_\Phi$, $\lambda_{H\Phi\Phi'}(\sin 2\theta)$,m_Ψ

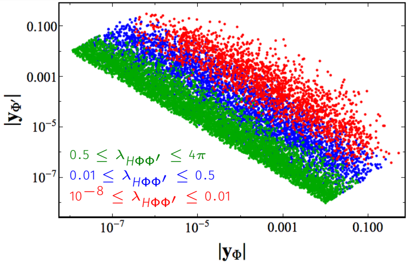
$\mathcal{M}_\nu$ is rank 2, so one massless ν and two massive

$$m_\nu^\pm \propto \left(|\mathbf{y}_\Phi|\;|\mathbf{y}_{\Phi'}| \pm |\mathbf{y}_\Phi \cdot \mathbf{y}_{\Phi'}^\dagger|\right) .$$

Yukawa vectors $\mathbf{y}_\Phi^{(\prime)}$ determined by low-energy data up to one parameter ζ which determines relative size

Majorana ν mass





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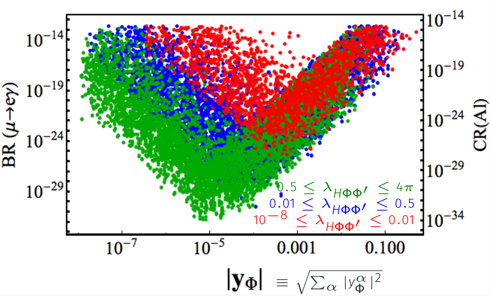
Lepton flavour violation: $\mu \to e$ transition

$$\mathrm{BR}(\mu \to e\,\gamma) = \frac{3\,\alpha_{\rm em}}{64\pi G_F^2} \left| \frac{y_\Phi^{\beta *}\, y_\Phi^{\alpha}}{m_{\eta^\pm}^2} f\left(\frac{m_\psi^2}{m_{\eta^\pm}^2}\right) + \frac{y_{\Phi'}^{\beta *}\, y_{\Phi'}^{\alpha}}{m_{\eta'^\pm}^2} f\left(\frac{m_\psi^2}{m_{\eta'^\pm}^2}\right) \right|^2$$

$$\mathrm{CR(Al)} \simeq [0.0077, 0.011] \times \mathrm{BR}(\mu \to e\gamma)$$ Dipole dominance

Only free parameters: masses m_ψ, $m_{\eta^\pm}$, and ζ



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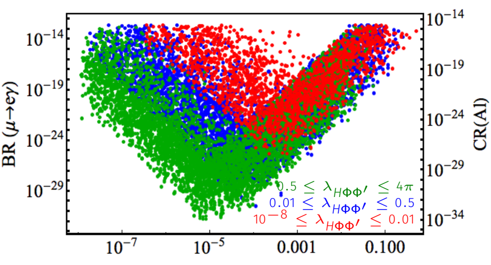
$$\mathrm{NO}: \quad \mathbf{y}_\Phi = \frac{\zeta}{\sqrt{2}}\left(\sqrt{m_{sol}}u_2^* \pm i\sqrt{m_{atm}}u_3^*\right) \qquad \mathbf{y}_{\Phi'} = \frac{1}{\zeta\sqrt{2}}\left(\sqrt{m_{sol}}u_2^* \mp i\sqrt{m_{atm}}u_3^*\right)$$

$$\mathrm{IO}: \quad \mathbf{y}_\Phi = \frac{\zeta}{\sqrt{2}}\left(\sqrt{m_{sol}}u_1^* \pm i\sqrt{m_{atm}}u_2^*\right) \qquad \mathbf{y}_{\Phi'} = \frac{1}{\zeta\sqrt{2}}\left(\sqrt{m_{sol}}u_1^* \mp i\sqrt{m_{atm}}u_2^*\right)$$



$|\mathbf{y}_\Phi| \equiv \sqrt{\sum_\alpha |y_\Phi^\alpha|^2}$

with u_i being the columns of the PMNS matrix

Using $f\left(m^2_{\eta^\pm}/m^2_\psi\right) \xrightarrow{m_{\eta^\pm}\to m_\psi} \frac{1}{12}$

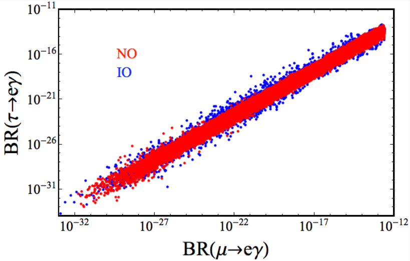
$$\mathrm{NO}: \quad 0.0003\,\frac{100\ \mathrm{GeV}}{m_{\eta'^\pm}} \lesssim \zeta \lesssim 4000\,\frac{m_{\eta^\pm}}{100\ \mathrm{GeV}}$$

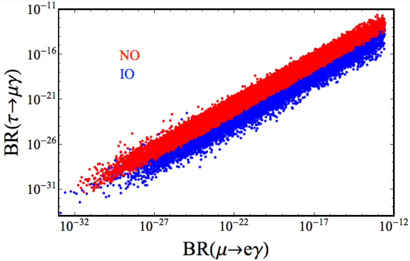
$$\mathrm{IO}: \quad 0.0004\,\frac{100\ \mathrm{GeV}}{m_{\eta'^\pm}} \lesssim \zeta \lesssim 3000\,\frac{m_{\eta^\pm}}{100\ \mathrm{GeV}}$$

Correlation between different LFV rates

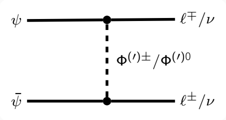
$$\text{NO}: \frac{\text{BR}(\tau \to e\,\gamma)}{\text{BR}(\mu \to e\,\gamma)} \approx 0.2 \quad \text{and} \quad \frac{\text{BR}(\tau \to \mu\,\gamma)}{\text{BR}(\mu \to e\,\gamma)} \approx 5$$

$$\text{IO}: \frac{\text{BR}(\tau \to e\,\gamma)}{\text{BR}(\mu \to e\,\gamma)} \approx \frac{\text{BR}(\tau \to \mu\,\gamma)}{\text{BR}(\mu \to e\,\gamma)} \approx 0.2\,,$$





DM s-wave annihilations into leptons and LFV



$$\xrightarrow{ch.lep.} \langle v\sigma_{\ell\ell}\rangle = \frac{1}{32\pi m_\psi^2}\left| y_\Phi^\alpha y_\Phi^{\beta*}\frac{m_\psi^2}{m_{\eta^\pm}^2 + m_\psi^2} - y_{\Phi'}^\alpha y_{\Phi'}^{\beta*}\frac{m_\psi^2}{m_{\eta'^\pm}^2 + m_\psi^2}\right|^2$$

Only depends on masses and ζ and thus strongly constrained by LFV

A conservative estimate

$$\frac{\sum_{\alpha,\beta}\langle v\sigma(\psi\bar{\psi}\to\ell_\alpha^-\ell_\beta^+,\nu_\alpha\nu_\beta)\rangle}{\langle v\sigma\rangle_{\rm th}} \lesssim 1\,(0.3)\times 10^{-6}\left(\frac{3\times10^{-26}\mathrm{cm}^3/\mathrm{s}}{\langle v\sigma\rangle_{\rm th}}\right)\left(\frac{m_\psi}{100\,\mathrm{GeV}}\right)^2$$

for $m_{\eta_0'} \simeq m_{\eta^\pm} \simeq m_\psi$. Larger scalar masses lead to a further suppression. This is confirmed by numerical scan with micrOMEGAs.

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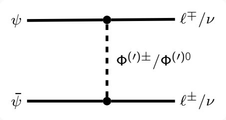

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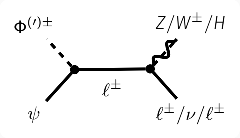
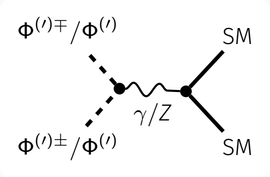
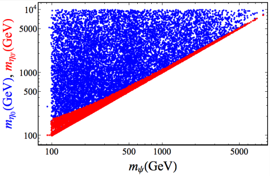
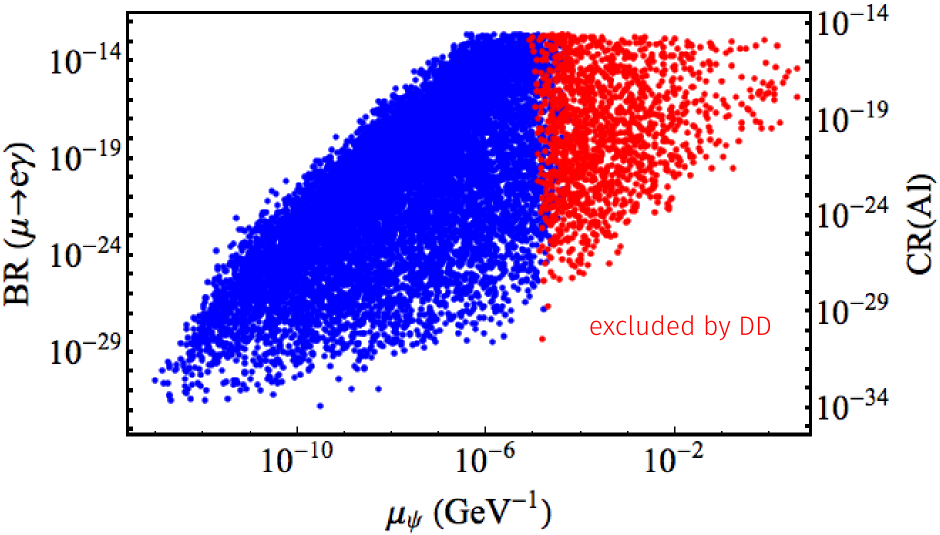
Annihilations into leptons too small: need coannihilation with scalars $\Phi^{(\prime)}$







Complementarity of LFV and DM direct detection



Conclusions

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DM - nucleus scattering only at 1-loop order (or higher)

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magnetic and electric dipole moment dominate
Higgs penguins are important for Majorana DM

Scotogenic model with Dirac fermion

fermionic DM requires coannihilation
interplay between LFV and direct detection

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Scotogenic model with Dirac fermion

fermionic DM requires coannihilation
interplay between LFV and direct detection

Thank you!