The Skotos (dark) connection of Neutrinos

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DM and ν origin story

Origin of neutrino mass and dark matter two pressing puzzles in *PPC* addressed by hidden sectors containing new particles/symmetries

Radiative connection: long history of radiative m_ν mechanisms
DM and m_ν are related radiatively?

Flavor/Horizontal symmetries:
Non-Abelian discrete symmetries still of continuous interest to explain PMNS

Complementarity:
Use DD, Colliders, Precision to constrain *DM*/BSM physics

The Dark connection of neutrinos?

Two main frameworks to connect neutrinos and *DM* in literature:

(*i*) *DM* identified as one of new particles required to give ν mass (Mass mechanism)

	Model	Scalars	Fermions	LFV	DM	LHC
1-Loop	Zee	$(\mathbf{1},\mathbf{1},+1)_{-2}\,,\,(\mathbf{1},\mathbf{2},+1/2)_0$		✓	✗	✓
	Ma	$(\mathbf{1},\mathbf{2},+1/2)_0$	$(\mathbf{1},\mathbf{1},0)_{+1}$	✓	✓	✓
2-Loops	Zee-Babu	$(\mathbf{1},\mathbf{1},+1)_{-2}\,,\,(\mathbf{1},\mathbf{1},+2)_{-2}$		✓	✗	✓
3-Loops	KNT	$(\mathbf{1},\mathbf{1},+1)_{-2}$	$(\mathbf{1},\mathbf{1},0)_{+1}$	✓	✓	✗

Table: Phenomenological implications of radiative $SU(3)_c \times SU(2)_L \times U(1)_Y$ neutrino mass models

(*ii*) *DM* associated with symmetries of ν sector (Lepton symmetries) i.e the mixing patterns and/or lepton number

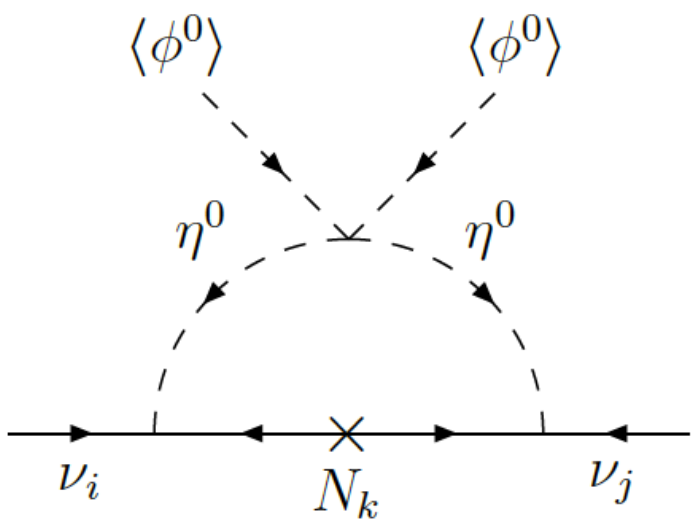
The Scotogenic model

Scotogenic Model = SM + 3 singlet Fermions ($N_{1,2,3}$) + scalar doublet (η) + dark Z_2

[Ma, hep-ph/0601225]

- Particles in loop odd under dark Z_2
- Majorana mass of N completes loop
- Mass splitting ($\lambda_5(\eta^\dagger\phi)^2$) makes loop finite
- Either η_0 or *N* are *DM* candidate
- The yukawas that enters into m_ν also generates

LFV processes however the bounds only constrain combination of yukawa coupling elements → cancelations possible → safe in Ma model



Discrete symmetry is usually put in by hand in Scotogenic theories
Masses of RH neutrino has to be assumed to be at TeV scale

This Talk

- Propose class of chiral models with anomaly-free solutions to SM + $U(1)_D$
- Explore $U(1)_D$ hidden sector with m_υ & *DM* generated through scotogenic mechanism
- Derive *DM* stability from gauge symmetry: unbroken residual symmetry of $U(1)_D$ plays the role of Z_2 in the Ma model to forbid tree-level neutrino mass and *DM* decay

U(1)$_D$ broken by only one singlet scalar that generates masses to all dark fermions: min scalar sector

Explore different *DM* phenomenology scenarios:
Majorana/Dirac Fermion *DM*
Scalar *DM* (singlet-doublet mixture)

Anomaly cancellations

Fermion mass

Minimality of scalar sector

Scotogenic mechanism

Anomaly-free chiral fermion models

- Interested in finding hidden sector models with anomaly-free min chiral fermions
- Focus on $U(1)_D$ gauge extension of SM under which SM fields are neutral
- Cancellation of mixed gauge-gravitational anomaly and cubic gauge anomaly imposes the following constraints (Diophantine equations) on charges assignments $\{q_i\}$

$$\sum_{i=1}^{12} q_i = 0 \qquad \sum_{i=1}^{12} q_i^3 = 0$$

- Since there is no new $SU(2)_L$, global Witten anomaly is not relevant in our case
- Require # of chiral fermions ≤ 8 in the anomaly-free chiral models
- List solutions that satisfy the condition of maximal charge ratio ≤ 7
- For each of these chiral models, investigate for minimal set of scalar fields that can give masses for all chiral fermions

Anomaly free chiral fermions

Model	Number of Fermions	(a,b,c)	Fermion States: Multiplicity$\times${charge}	Scalar States: Multiplicity$\times${charge}
1	6	$(-1,0,-3)$	$3\times\{1\}+2\times\{-4\}+1\times\{5\}$	$1\times\{3\}+1\times\{6\}$
2	6	$(-1,-4,-1)$	$1\times\{1\}+1\times\{-2\}+1\times\{-3\}+2\times\{5\}+1\times\{-6\}$	$1\times\{1\}+1\times\{2\}$
3	7	$(-1,-2,-1)$	$1\times\{-1\}+2\times\{-2\}+3\times\{3\}+1\times\{-4\}$	$1\times\{1\}+1\times\{2\}$
4	8	$(-2,-1,-2)$	$2\times\{1\}+1\times\{2\}+1\times\{3\}+2\times\{-4\}+1\times\{-5\}+1\times\{6\}$	$1\times\{2\}$
5	8	$(-1,-2,-4)$	$1\times\{-1\}+3\times\{-2\}+1\times\{3\}+1\times\{5\}+1\times\{6\}+1\times\{-7\}$	$1\times\{4\}$
6	8	$(-2,-5,-1)$	$1\times\{2\}+1\times\{-3\}+1\times\{-4\}+1\times\{5\}+1\times\{-6\}+2\times\{7\}+1\times\{-8\}$	$1\times\{1\}$
7	8	$(-1,-4,-7)$	$1\times\{-2\}+2\times\{-3\}+1\times\{-4\}+1\times\{5\}+1\times\{9\}+1\times\{10\}+1\times\{-12\}$	$1\times\{7\}$
8	8	$(-2,-7,-1)$	$1\times\{3\}+1\times\{-4\}+1\times\{-5\}+1\times\{6\}+1\times\{-8\}+2\times\{9\}+1\times\{-10\}$	$1\times\{1\}$
9	8	$(-1,-4,-8)$	$2\times\{-2\}+1\times\{-3\}+1\times\{5\}+1\times\{-6\}+1\times\{10\}+1\times\{11\}+1\times\{-13\}$	$1\times\{8\}$
10	8	$(-1,-8,-5)$	$1\times\{-2\}+1\times\{-3\}+1\times\{-4\}+1\times\{-7\}+2\times\{9\}+1\times\{12\}+1\times\{-14\}$	$1\times\{5\}$
11	8	$(-3,-8,-1)$	$1\times\{4\}+1\times\{-5\}+1\times\{-6\}+1\times\{7\}+1\times\{-10\}+2\times\{11\}+1\times\{-12\}$	$1\times\{1\}$
12	8	$(-6,-1,-2)$	$1\times\{-3\}+1\times\{5\}+1\times\{7\}+1\times\{-9\}+1\times\{10\}+2\times\{-12\}+1\times\{14\}$	$1\times\{2\}$
13	8	$(-2,-5,-10)$	$1\times\{-3\}+2\times\{-4\}+1\times\{-6\}+1\times\{7\}+1\times\{13\}+1\times\{14\}+1\times\{-17\}$	$1\times\{10\}$
14	8	$(-3,-10,-1)$	$1\times\{5\}+1\times\{-6\}+1\times\{-7\}+1\times\{8\}+1\times\{-12\}+2\times\{13\}+1\times\{-14\}$	$1\times\{1\}$
15	8	$(-2,-5,-11)$	$2\times\{-3\}+1\times\{-4\}+1\times\{7\}+1\times\{-8\}+1\times\{14\}+1\times\{15\}+1\times\{-18\}$	$1\times\{11\}$
16	8	$(-4,-1,-11)$	$1\times\{3\}+2\times\{5\}+1\times\{6\}+1\times\{-8\}+1\times\{-14\}+1\times\{-16\}+1\times\{19\}$	$1\times\{11\}$
17	8	$(-4,-11,-1)$	$1\times\{6\}+1\times\{-7\}+1\times\{-8\}+1\times\{9\}+1\times\{-14\}+2\times\{15\}+1\times\{-16\}$	$1\times\{1\}$
18	8	$(-5,-8,-7)$	$1\times\{-3\}+1\times\{-4\}+1\times\{-6\}+1\times\{-10\}+2\times\{13\}+1\times\{17\}+1\times\{-20\}$	$1\times\{7\}$
19	8	$(-4,-1,-13)$	$2\times\{3\}+1\times\{5\}+1\times\{-8\}+1\times\{10\}+1\times\{-16\}+1\times\{-18\}+1\times\{21\}$	$1\times\{13\}$
20	8	$(-8,-1,-2)$	$1\times\{-5\}+1\times\{7\}+1\times\{9\}+1\times\{-11\}+1\times\{14\}+2\times\{-16\}+1\times\{18\}$	$1\times\{2\}$
21	8	$(-2,-7,-13)$	$1\times\{-4\}+2\times\{-5\}+1\times\{-8\}+1\times\{9\}+1\times\{17\}+1\times\{18\}+1\times\{-22\}$	$1\times\{13\}$
22	8	$(-4,-13,-1)$	$1\times\{7\}+1\times\{-8\}+1\times\{-9\}+1\times\{10\}+1\times\{-16\}+2\times\{17\}+1\times\{-18\}$	$1\times\{1\}$
23	8	$(-2,-7,-14)$	$2\times\{-4\}+1\times\{-5\}+1\times\{9\}+1\times\{-10\}+1\times\{18\}+1\times\{19\}+1\times\{-23\}$	$1\times\{14\}$
24	8	$(-5,-12,-3)$	$1\times\{4\}+1\times\{-7\}+1\times\{-10\}+1\times\{13\}+1\times\{-14\}+2\times\{17\}+1\times\{-20\}$	$1\times\{3\}$
25	8	$(-5,-14,-1)$	$1\times\{8\}+1\times\{-9\}+1\times\{-10\}+1\times\{11\}+1\times\{-18\}+2\times\{19\}+1\times\{-20\}$	$1\times\{1\}$
26	8	$(-2,-9,-15)$	$1\times\{-4\}+2\times\{-7\}+1\times\{-8\}+1\times\{11\}+1\times\{19\}+1\times\{22\}+1\times\{-26\}$	$1\times\{15\}$
27	8	$(-4,-15,-3)$	$1\times\{5\}+1\times\{-8\}+1\times\{-11\}+1\times\{14\}+1\times\{-16\}+2\times\{19\}+1\times\{-22\}$	$1\times\{3\}$
28	8	$(-2,-15,-9)$	$1\times\{-4\}+1\times\{-5\}+1\times\{-8\}+1\times\{-13\}+2\times\{17\}+1\times\{22\}+1\times\{-26\}$	$1\times\{9\}$
29	8	$(-10,-1,-2)$	$1\times\{-7\}+1\times\{9\}+1\times\{11\}+1\times\{-13\}+1\times\{18\}+2\times\{-20\}+1\times\{22\}$	$1\times\{2\}$
30	8	$(-7,-12,-9)$	$1\times\{-4\}+1\times\{-5\}+1\times\{-10\}+1\times\{-14\}+2\times\{19\}+1\times\{23\}+1\times\{-28\}$	$1\times\{9\}$
31	8	$(-11,-2,-4)$	$1\times\{-5\}+1\times\{9\}+1\times\{13\}+1\times\{-17\}+1\times\{18\}+2\times\{-22\}+1\times\{26\}$	$1\times\{4\}$
32	8	$(-12,-1,-2)$	$1\times\{-9\}+1\times\{11\}+1\times\{13\}+1\times\{-15\}+1\times\{22\}+2\times\{-24\}+1\times\{26\}$	$1\times\{2\}$
33	8	$(-8,-13,-11)$	$1\times\{-5\}+1\times\{-6\}+1\times\{-10\}+1\times\{-16\}+2\times\{21\}+1\times\{27\}+1\times\{-32\}$	$1\times\{11\}$
34	8	$(-11,-6,-12)$	$1\times\{5\}+1\times\{7\}+1\times\{10\}+1\times\{17\}+2\times\{-22\}+1\times\{-29\}+1\times\{34\}$	$1\times\{12\}$
35	8	$(-13,-2,-4)$	$1\times\{-7\}+1\times\{11\}+1\times\{15\}+1\times\{-19\}+1\times\{22\}+2\times\{-26\}+1\times\{30\}$	$1\times\{4\}$
36	8	$(-14,-1,-2)$	$1\times\{-11\}+1\times\{13\}+1\times\{15\}+1\times\{-17\}+1\times\{26\}+2\times\{-28\}+1\times\{30\}$	$1\times\{2\}$
37	8	$(-14,-3,-6)$	$1\times\{-5\}+1\times\{11\}+1\times\{17\}+1\times\{22\}+1\times\{-23\}+2\times\{-28\}+1\times\{34\}$	$1\times\{6\}$
38	8	$(-15,-2,-4)$	$1\times\{-9\}+1\times\{13\}+1\times\{17\}+1\times\{-21\}+1\times\{26\}+2\times\{-30\}+1\times\{34\}$	$1\times\{4\}$

Findings

- Out of 38 solutions, a couple with 6 and only one with 7 fermions requiring at least two Higgs fields to generate masses for all the new fermions

- For models 2, 3, 6, 8, 11, 14, 17, 22, and 25 no residual symmetry exists to stabilize DM after $U(1)_D$ spontaneous symmetry breaking

- Scotogenic realization of models 7, 9, 10, 12, 13, 15, 16, 18-21, 23, 24, 26-38 would require more than three scalar multiplets

- We choose Model 4/5 (A/B) in the Table with # 8 fermions and min scalar state as representative models to implement Scotogenic mechanism for m_ν and perform *DM* analysis

- The nature of the residual symmetry $U(1)_D \to Z_N$ depends on the charge assignment of scalar η responsible for the breaking of $U(1)_D$ symmetry

- For Model-A (B), the scalar field η has a charge 2(4) under dark symmetry, remnant symmetry corresponds to discrete symmetry Z_2 (Z_4)

Representative models

Anomaly-free charge assignments (multiplicity × charge)

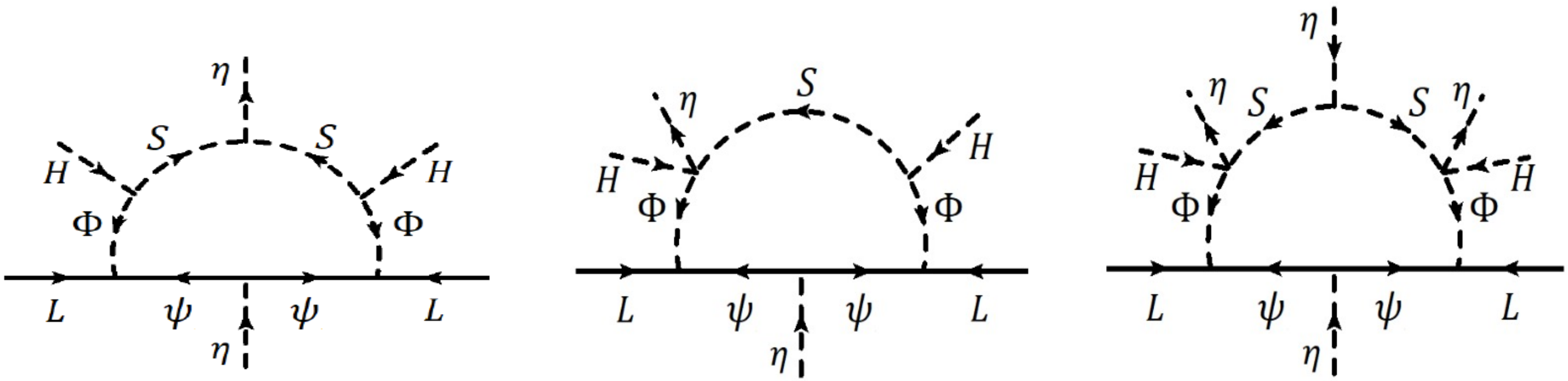
Model A: 2 × {1} + 2 × {−4} + 1 × {2} + 1 × {3} + 1 × {−5} + 1 × {6}

Model B: 1 × {1} + 3 × {2} + 1 × {-3} + 1 × {-5} + 1 × {−6} + 1 × {7}

Multiplets	Model-A	Model-B
η	$(1, 0, 2)$	$(1, 0, 4)$
S	$(1, 0, 1)$	$(1, 0, 2)$
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	$(2, \frac{1}{2}, -1)$	$(2, \frac{1}{2}, -2)$

BSM scalar sector of Model-A(B) with quantum numbers under $SU(2)_L \times U(1)_Y \times U(1)_D$

Neutrino mass generation



Representative Feynman diagrams for 1 loop generation of m_ν

Three scalar fields are needed to connect the loop diagrams

Lightest field in the loop could be DM

Since there are only two Majorana fermions circulating in the loops, only two neutrinos will acquire masses at 1-loop → lightest neutrino mass is essentially massless (higher order loop corrections inducing a very tiny mass)

Formalism

- Scalar potential for Model A

$$V = -\mu_H^2 H^\dagger H - \mu_\eta^2 \eta^* \eta + \mu_\Phi^2 \Phi^\dagger \Phi + \mu_S^2 S^* S + (\mu_{S\Phi} H^\dagger \Phi S^* + \text{h.c.}) + (\mu_{S\eta} S^2 \eta^* + \text{h.c.})$$
$$+ \sum_{\varphi}^{\{H,\eta,\Phi,S\}} \lambda_\varphi (\varphi^\dagger \varphi)^2 + \lambda_{H\eta} H^\dagger H \eta^* \eta + \lambda_{H\Phi} H^\dagger H \Phi^\dagger \Phi + \lambda'_{H\Phi} H^\dagger \Phi \Phi^\dagger H + \lambda_{\eta\Phi} (\Phi^\dagger \Phi) \eta^* \eta$$
$$+ \lambda_{HS} (H^\dagger H) S^* S + \lambda_{\eta S} \eta^* \eta S^* S + \lambda_{\Phi S} (\Phi^\dagger \Phi) S^* S.$$

- $U(1)_D$ gauge symmetry is broken down to Z_2 ensuring *DM* stability
- Once $U(1)_D$ is spontaneously broken corresponding gauge boson *Z′* acquires its mass and interacts with SM through kinetic term
- Once η field develops VEV fermion sector contains two massive Majorana fermions {N1, N2} and three massive Dirac fermions {ξ, ζ1, ζ2}
- Yukawa Lagrangian (fermionic dark matter)

$$-\mathcal{L}_Y = y \bar{L} \widetilde{\Phi} \Psi_1 + \frac{f}{2} \bar{\Psi}_1^c \Psi_1 \eta^* + f' \bar{\Psi}_2^c \Psi_{-4} \eta + f'' \bar{\Psi}_6^c \Psi_{-4} \eta^* + f''' \bar{\Psi}_3^c \Psi_{-5} \eta$$
$$+ \kappa \bar{\Psi^c}_{-4} \Psi_3 S + \kappa' \bar{\Psi^c}_{-5} \Psi_6 S^* + \text{h.c.}$$

Masses and mixings

- Scalar doublet *H* and η mix and is defined by h, h' and mixing angle θ

$$\begin{pmatrix} h \\ h' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \sigma \\ \eta_r \end{pmatrix} \quad , \qquad \sin 2\theta = \frac{2\lambda_{H\eta} v_D v_H}{m_{h'}^2 - m_h^2}.$$

- For mixing between Re(ϕ^0) and Re(S) with mass eigen states H_1 and H_2:

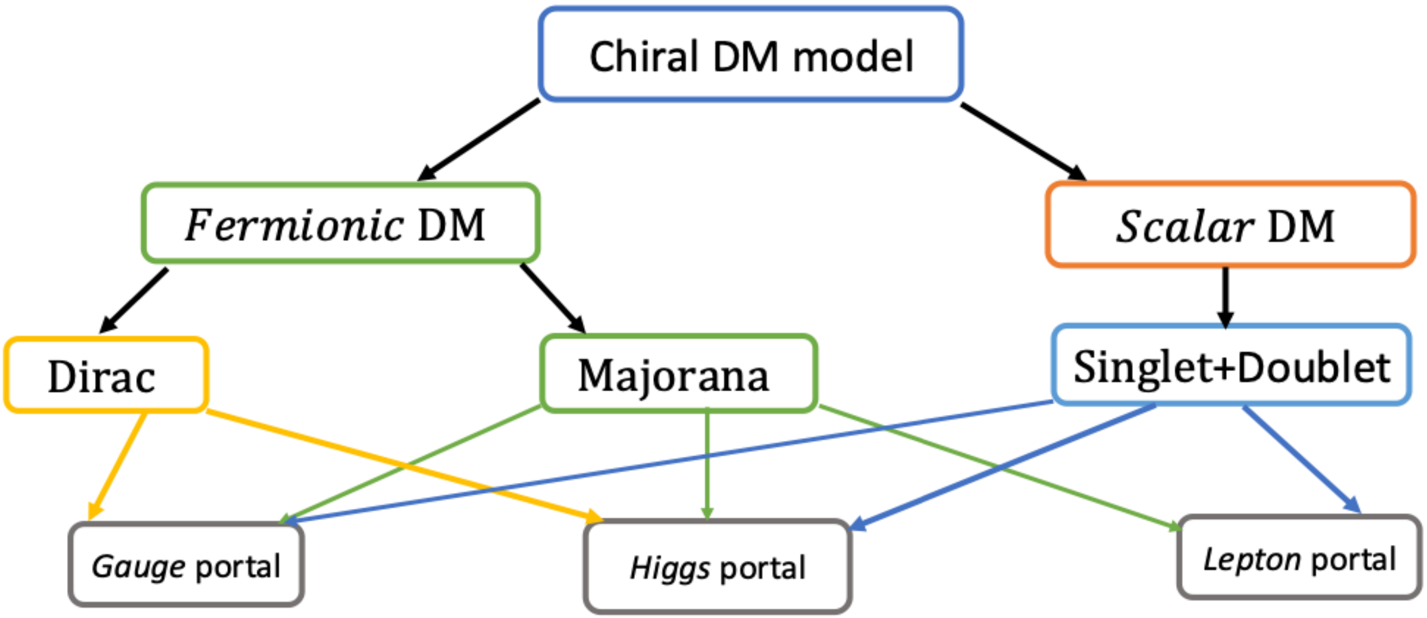
$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \mathrm{Re}(\phi^0) \\ \mathrm{Re}(S) \end{pmatrix} \quad , \qquad \sin 2\alpha = \frac{\sqrt{2}\mu_{S\Phi} v_H}{m_{H_2}^2 - m_{H_1}^2}.$$

- For mixing between Im(ϕ^0) and Im(S) with mass eigen states A_1 and A_2:

$$\begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \mathrm{Im}(\phi^0) \\ \mathrm{Im}(S) \end{pmatrix}$$

$$\sin 2\beta = \frac{\sqrt{2}\mu_{S\Phi} v_H}{m_{A_1}^2 - m_{A_2}^2}.$$

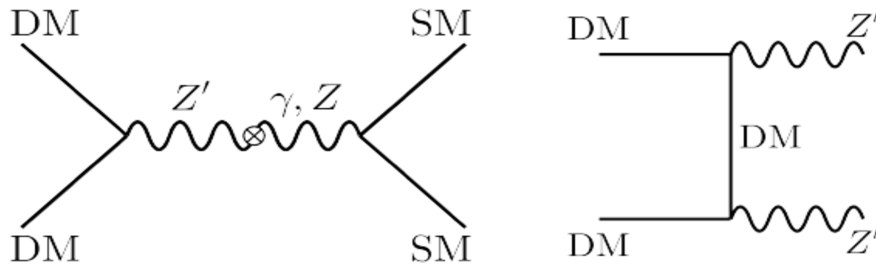
All possible DM candidates in this scenario



Fermionic *DM* is less explored in Scotogenic scenarios!

Fermion *DM* phenomenology (gauge portal)

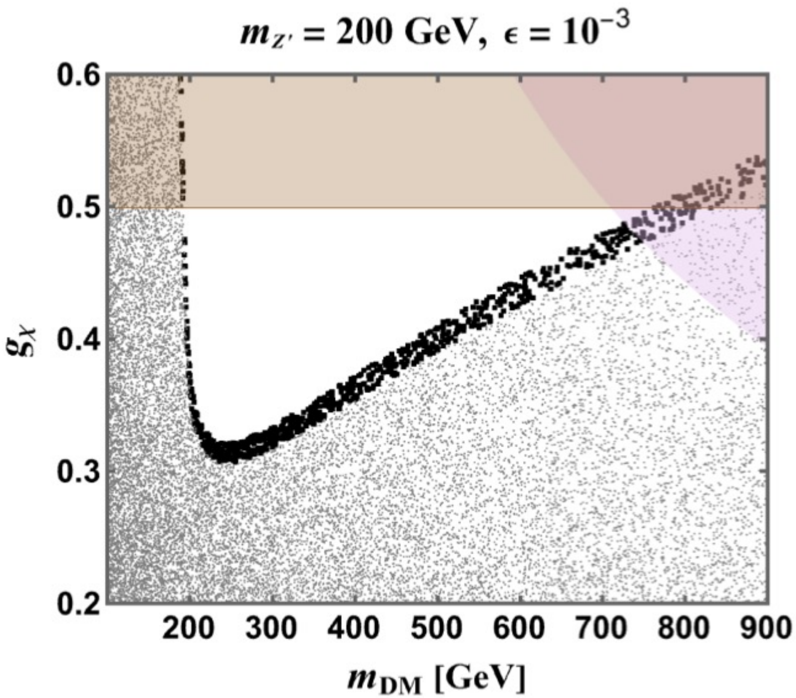
$2m_{DM} < m_{h', h}$

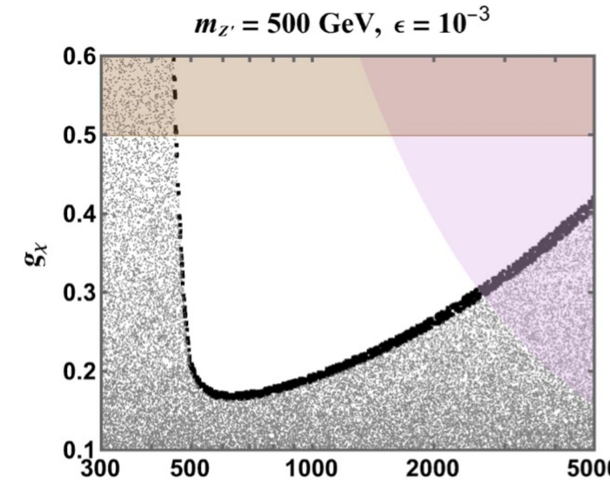


Feynman diagrams that contribute to the annihilation of Majorana DM

- *DM* coupling with gauge boson Z' would lead to dominant annihilation modes
- For $m_{DM} > m_{Z'}$, the dominant annihilation channel is *DM DM* → Z' Z' (secluded DM)
- For Majorana *DM* annihilation cross section is p-wave suppressed since DM coupling with Z' is axial-vector type
- For Dirac *DM* coupling with gauge boson can be vector type so the annihilation rate is not suppressed (s-wave)

Fermion *DM* phenomenology (gauge portal)





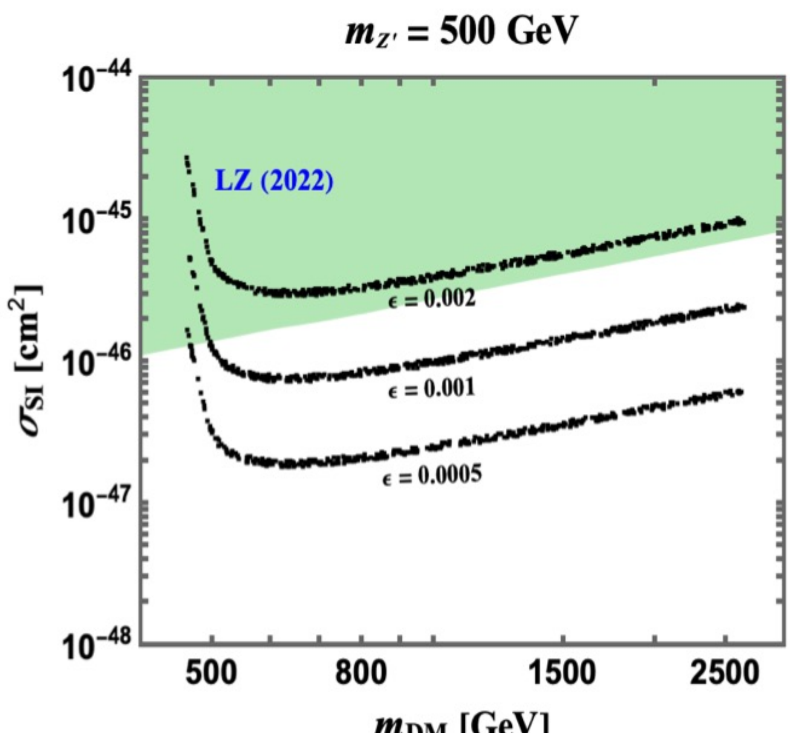


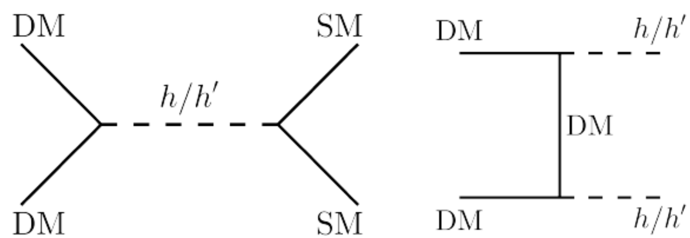
Fig: Parameter space in gauge coupling (g_χ) vs. m_{DM} plane with black dotted points consistent with the relic density constraint Ωh^2 = 0.12 ± 0.012 for the Majorana (L) and Dirac (R) DM. The grey-colored data points are excluded from the overabundance of DM. The brown (pink)-shaded region is excluded by the perturbativity bound on the gauge coupling (Yukawa coupling).

Corr Direct Detection plot is shown

Fermionic *DM* pheno (Higgs portal)

$m_{Z'} \ll m_{DM}$

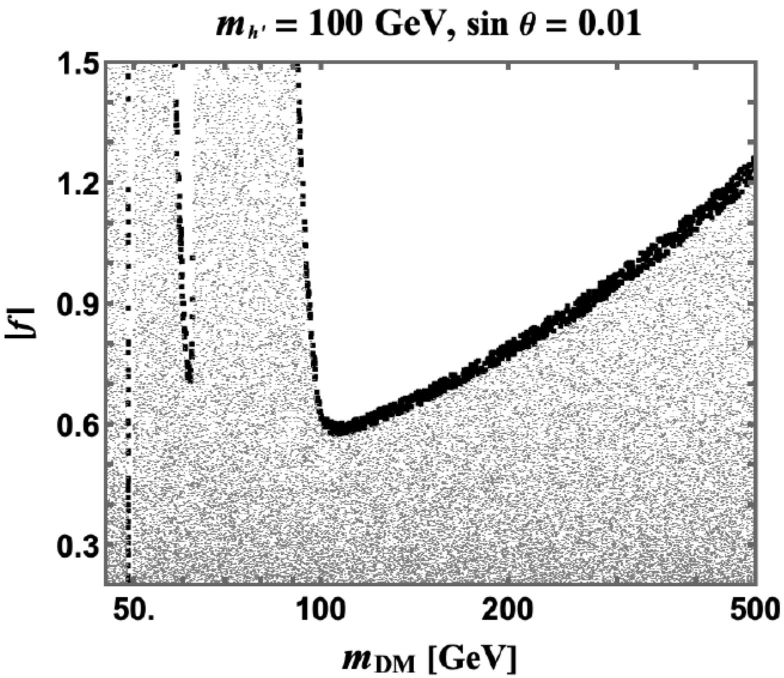
- *DM* coupling with neutral scalars h, h' lead to dominant annihilation modes



- Scalar portal annihilation modes are particularly important when $m_{DM} \sim m_{h/h'}$
- when *DM* is heavier than h, h' fields *DM* pair annihilate into $h\ h$, $h\ h'$, and $h'\ h'$
- However, since *DM* coupling with SM Higgs h is suppressed by $sin\theta$, dominant annihilation channel is *DM DM* $\rightarrow h'\ h'$
- Thus in this region of parameter space, *DM* can be identified as secluded *DM*

- LFV safe! Yukawas entering LFV process distinct than Yukawas needed here to satisfy bounds applicable in fermionic *DM* sector

Fermionic *DM* pheno (Higgs portal)



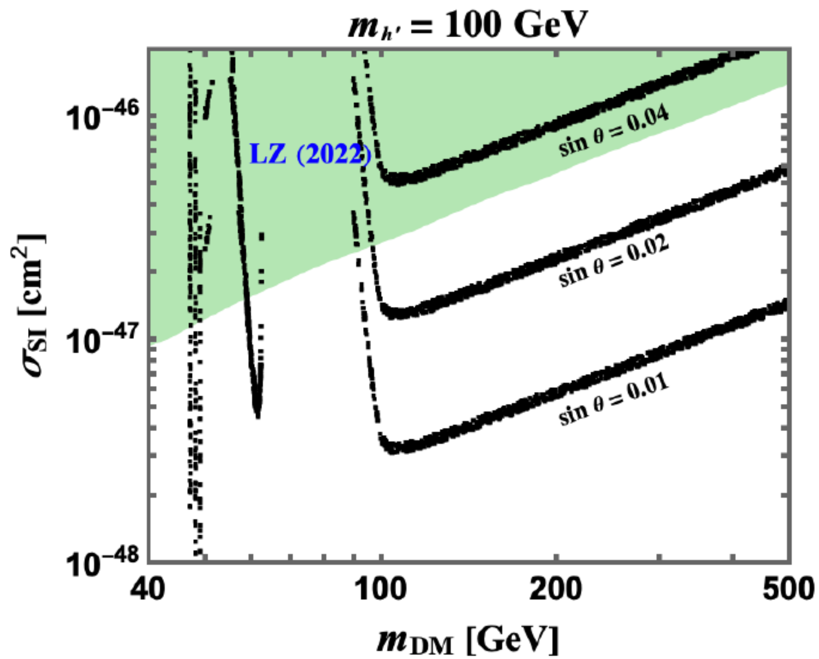


Fig L: Parameter space in Yukawa coupling (f) vs. m_{DM} plane consistent with relic density constraint for Majorana *DM*

Fig R: Spin independent cross section vs. m_{DM} consistent with DD constraints for Majorana *DM*

- Mixing angle sin θ > 0.04 is excluded from the LZ experiment for $m_{h'}$= 100 GeV.

Fermion *DM* phenomenology (Dirac)

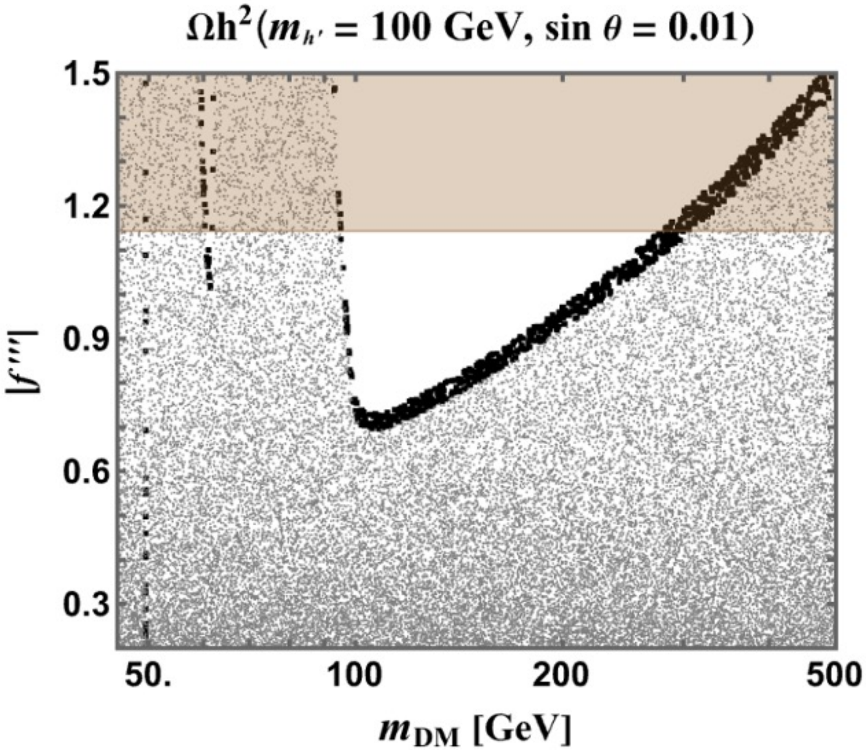


Fig: Parameter space in Yukawa coupling (f''') vs. m_{DM} plane consistent with relic density constraint for Dirac *DM*

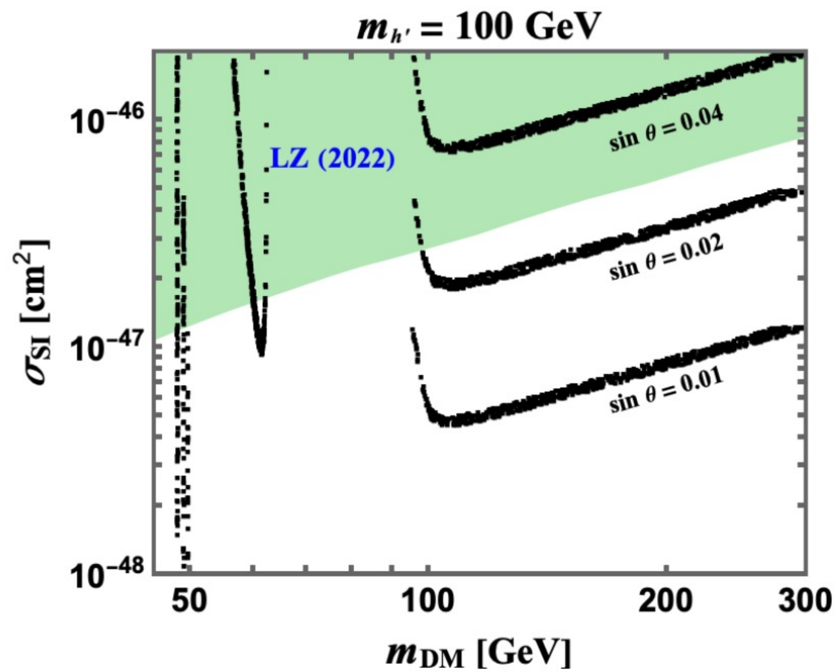


Fig: Spin independent cross section vs. m_{DM} consistent with DD constraints for Dirac *DM*

- Since *DM* coupling with neutral scalar states *h* and *h'* is similar for both Majorana and Dirac *DM*, corresponding *DM* phenomenology is also similar for both cases

Fermionic *DM* phenomenology (low mass)

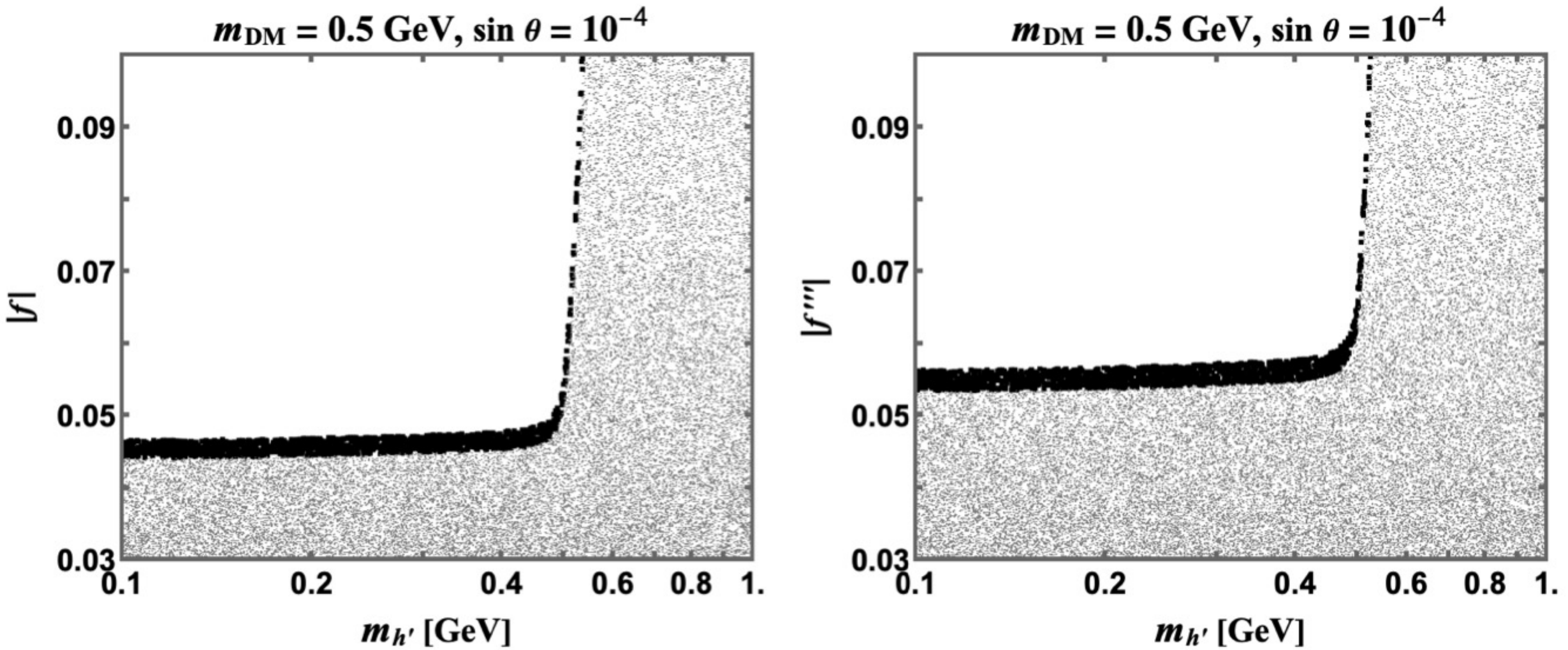
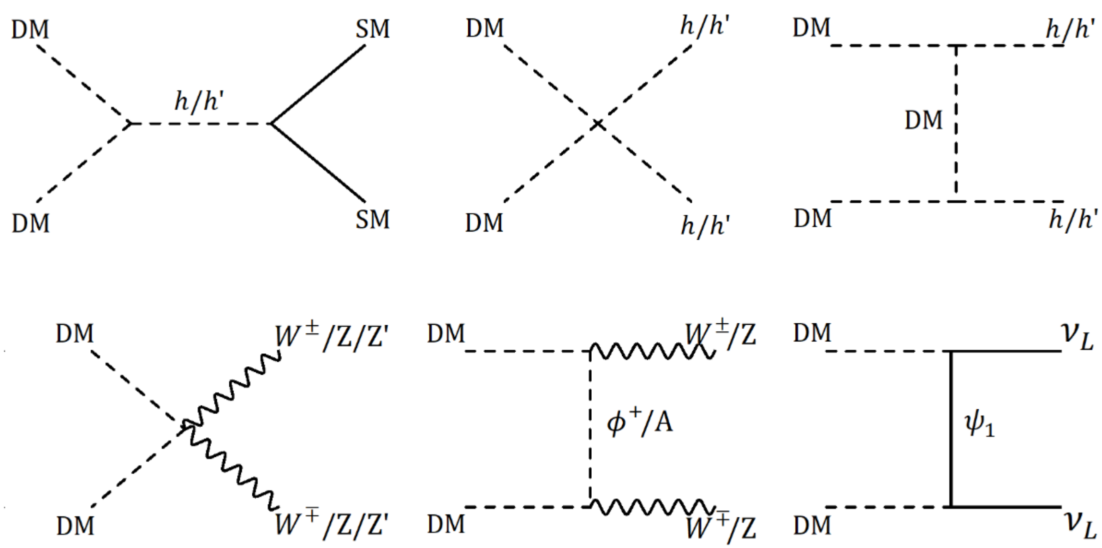


Fig: Parameter space in Yukawa coupling (f, f ''') vs. scalar mass ($m_{h'}$) plane consistent with the relic density constraint for the Majorana (left) and Dirac *DM* for low mass region

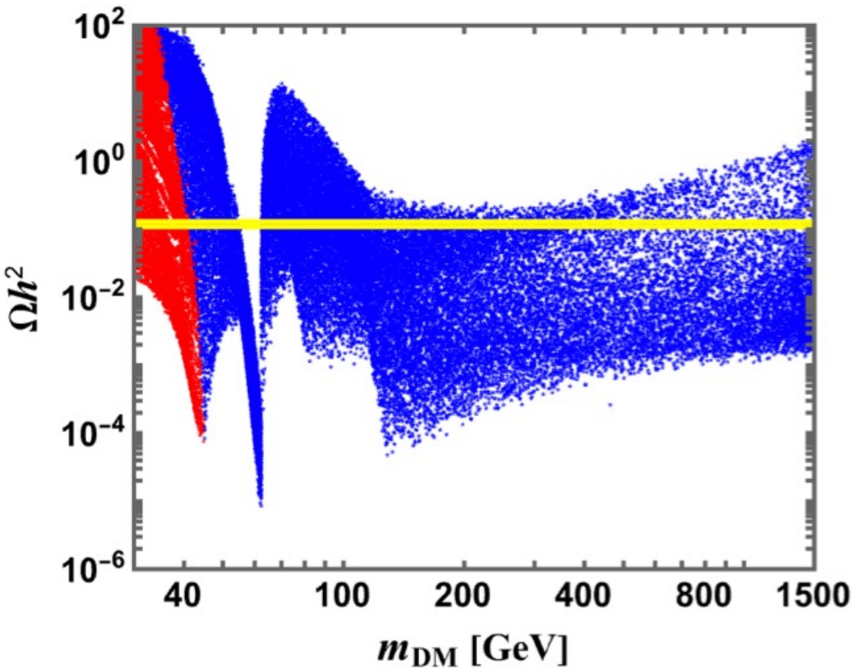
Scalar *DM* phenomenology

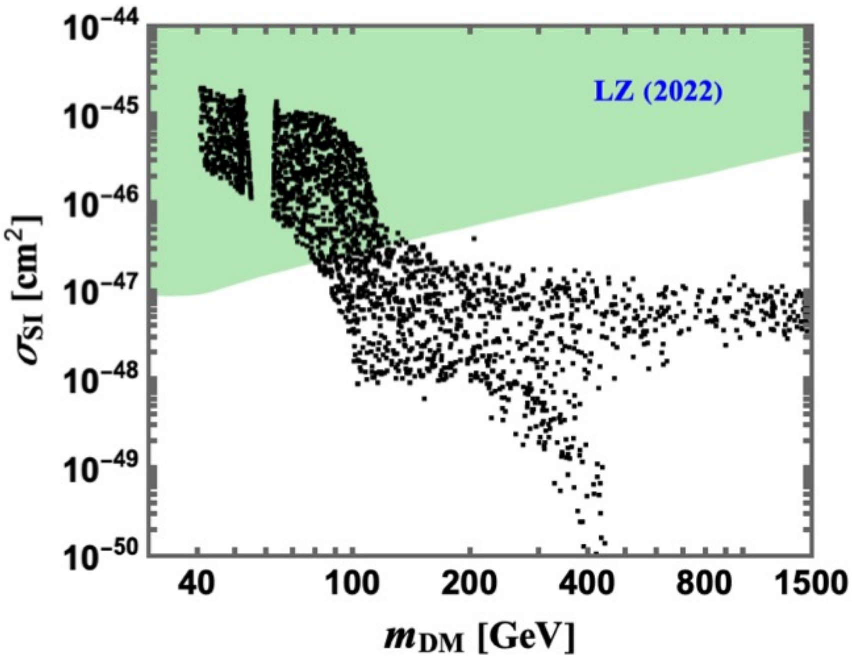
- To generate m_ν need nonzero mixing between scalar doublet Φ and singlet scalar S
- Scalar *DM* will be an admixture of neutral components of Φ and S
- Lightest neutral state among $\{H_1, H_2, A_1, A_2\}$ qualifies as *DM* (choose H_1 to be *DM*)
- A pair of scalar *DM* H_1 can annihilate through modes shown below



Feynman diagrams that contribute to the annihilation of scalar *DM*

Scalar *DM* phenomenology





Fig(L): Relic density of DM as a function of m_{DM}. The red (blue)-colored data points are excluded (allowed) by the constraints from the Z-decay width measurements. The yellow-shaded region indicates the Planck relic density constraints.

Fig (R): DM-nucleon spin independent cross section. The green-shaded region denotes the excluded parameter space by LZ. Here, we set sin α = 0.99

Take Home points

- Proposed a class of chiral models for DM based on a $U(1)_D$ gauge symmetry acting on a dark sector
- Explore for charge assignments satisfying anomaly free chiral hidden sector along with minimalized scalar sector to incorporate *DM*
- With simplifying restrictions on the charges of the fermions, we have identified 38 chiral models
- Owing to its chiral nature U(1) protects dark matter mass which arises after SSB
- An unbroken discrete symmetry Z_N ensures the stability of the DM
- Chiral non-abelian $SU(3)\times SU(2)$ is broken to $U(1)_D$
- Models show possible *DM* candidates could be either Fermionic type (more interesting, less explored scenario) or scalar type (singlet-doublet)
- Fermionic *DM* includes both Majorana and Dirac *DM* with scalar and gauge portals
- *DM* pheno containing different mass regions explored accessible to DD experiments!

Thank you for your attention