

Dark Connection of v

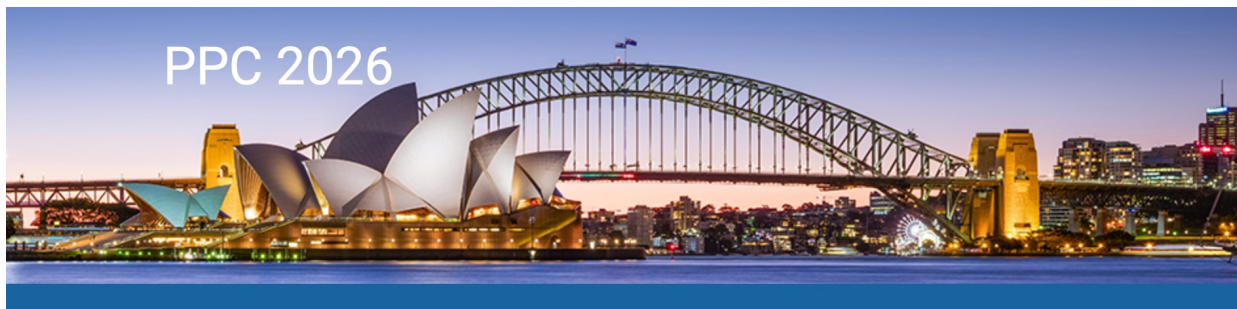
Shreyashi Chakdar

schakdar@holycross.edu

College of the Holy Cross, MA



with K.S. Babu and Vishnu P.K
Based on ([JCAP 02 \(2025\) 010](#))



The **Dark** connection of neutrinos?

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

(i) *DM* identified with one of new particles needed 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 to symmetries of ν sector (**Lepton symmetries**) i.e the mixing patterns and/or lepton number

Chiral Advantage: Mass protection

Vector-Like Models	$\mathcal{L} \supset m_\chi \chi \chi^c$	 Implication: Bare mass m_χ is unprotected by gauge symmetries and naturally driven to the Planck scale ($M_{\text{Pl}} \sim 10^{19}$ GeV). WIMP phenomenology ($\sim$ TeV) requires severe fine-tuning.
Chiral Models	$\mathcal{L} \supset y_\chi \chi \chi^c \langle \eta \rangle$	 Implication: Bare mass is forbidden. Mass is dynamically generated via symmetry breaking and protected down to the $U(1)_D$ scale, mirroring the SM's electroweak protection of the top quark.

Anomaly cancellations

Minimality of Scalar sector

Dark matter



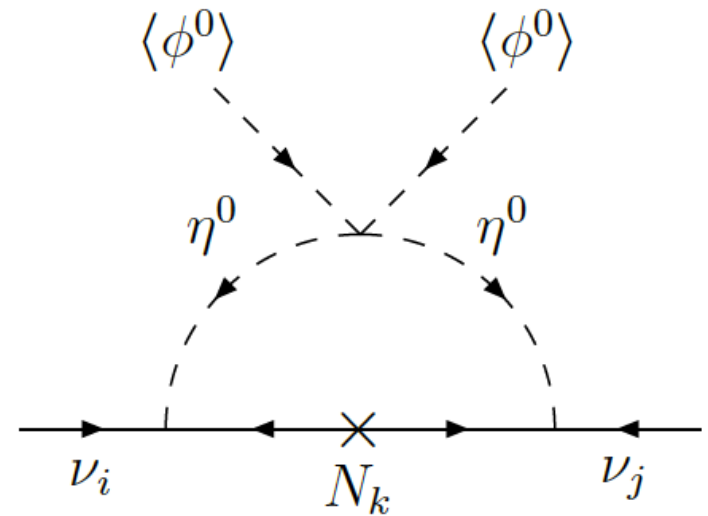
Neutrino mass

The Scotogenic model

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

[[hep-ph/0601225](https://arxiv.org/abs/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 $\rightarrow$ cancelations possible $\rightarrow$ safe in this 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 DM & m_ν generated through scotogenic mechanism
- Derive DM stability from gauge symmetry: unbroken residual symmetry of $U(1)_D$ plays role of Z_2 in scotogenic model to forbid tree-level m_ν and DM decay

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

Explore different DM phenomenology scenarios:

Majorana/Dirac Fermion DM

Scalar DM (singlet-doublet mixture)

Anomaly-free chiral fermion models

The Anomaly Constraints

For a dark sector with M left-handed Weyl fermions and $U(1)_D$ charges q_i :

$$\text{Mixed Gauge-Gravitational: } \sum_{i=1}^M q_i = 0$$

$$\text{Cubic Gauge Anomaly: } \sum_{i=1}^M q_i^3 = 0$$

Condition: All q_i must be rational (rescaled to integers), and vector-like pairs ($q_k = -q_l$) must be removed to ensure a purely chiral theory.

The $SU(3) \times SU(2)$ Progenitor

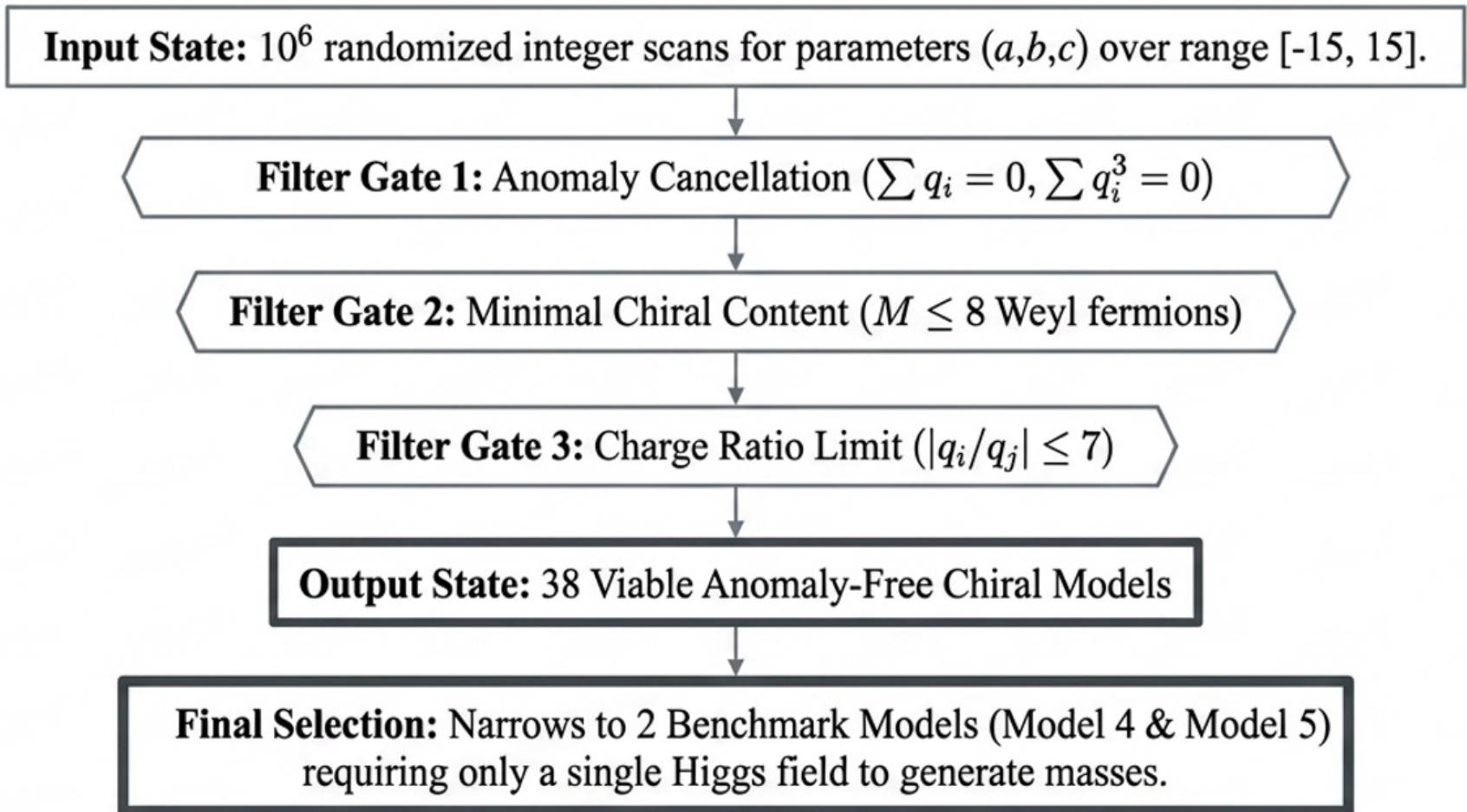
Start with a simple, chiral non-Abelian gauge theory identical to a single SM family (without hypercharge):

$$Q'(3, 2) = \begin{pmatrix} u'_1 & u'_2 & u'_3 \\ d'_1 & d'_2 & d'_3 \end{pmatrix}, \quad L'(1, 2) = \begin{pmatrix} \nu' \\ \ell' \end{pmatrix}$$

$$\bar{U}'(3^*, 1) = (\bar{u}'_1, \bar{u}'_2, \bar{u}'_3), \quad \bar{D}'(3^*, 1) = (\bar{d}'_1, \bar{d}'_2, \bar{d}'_3)$$

12 Weyl fermion structure: anomaly free chiral $U(1)_D$ upon SSB, naturally cancelling Witten anomaly

Model Derivation: The Computational Filter



Anomaly free chiral fermions

Fermion States: Multiplicity $\times$ {charge}	Scalar States: Multiplicity $\times$ {charge}
$3 \times \{1\} + 2 \times \{-4\} + 1 \times \{5\}$	$1 \times \{3\} + 1 \times \{6\}$
$1 \times \{1\} + 1 \times \{-2\} + 1 \times \{-3\} + 2 \times \{5\} + 1 \times \{-6\}$	$1 \times \{1\} + 1 \times \{2\}$
$1 \times \{-1\} + 2 \times \{-2\} + 3 \times \{5\} + 1 \times \{-4\}$	$1 \times \{1\} + 1 \times \{2\}$
$2 \times \{1\} + 1 \times \{2\} + 1 \times \{3\} + 2 \times \{-4\} + 1 \times \{-5\} + 1 \times \{6\}$	$1 \times \{2\}$
$1 \times \{-1\} + 3 \times \{-2\} + 1 \times \{3\} + 1 \times \{5\} + 1 \times \{6\} + 1 \times \{-7\}$	$1 \times \{4\}$
$2 \times \{1\} + 1 \times \{2\} + 1 \times \{3\} + 2 \times \{-4\} + 1 \times \{-5\} + 1 \times \{6\}$	$1 \times \{2\}$
$1 \times \{-1\} + 3 \times \{-2\} + 1 \times \{3\} + 1 \times \{5\} + 1 \times \{6\} + 1 \times \{-7\}$	$1 \times \{4\}$
$2 \times \{-2\} + 1 \times \{-3\} + 1 \times \{5\} + \{-6\} + 1 \times \{10\} + 1 \times \{11\} + 1 \times \{-18\}$	$1 \times \{8\}$
$2 \times \{-2\} + 1 \times \{-3\} + 4 \times \{-7\} + 2 \times \{9\} + 1 \times \{12\} + 1 \times \{-12\}$	$1 \times \{8\}$
$1 \times \{-4\} + 1 \times \{-3\} + 6 \times \{7\} + 1 \times \{-10\} + 2 \times \{11\} + 1 \times \{-14\}$	$1 \times \{5\}$
$1 \times \{-4\} + 1 \times \{1\} + \{-7\} + 1 \times \{9\} + 1 \times \{-10\} + 2 \times \{13\} + 1 \times \{-14\}$	$1 \times \{10\}$
$1 \times \{-3\} + 2 \times \{1\} + \{-6\} + 1 \times \{7\} + 1 \times \{-12\} + 2 \times \{14\} + 1 \times \{-17\}$	$1 \times \{10\}$
$1 \times \{-3\} + 1 \times \{4\} + \{-4\} + 1 \times \{8\} + 1 \times \{-14\} + 1 \times \{15\} + 1 \times \{-16\}$	$1 \times \{11\}$
$1 \times \{-5\} + 1 \times \{1\} + \{-7\} + 1 \times \{7\} + 1 \times \{-14\} + 1 \times \{16\} + 1 \times \{-18\}$	$1 \times \{11\}$
$1 \times \{6\} + 1 \times \{11\} + \{-8\} + 1 \times \{9\} + 1 \times \{-14\} + 2 \times \{17\} + 1 \times \{-20\}$	$1 \times \{7\}$

Isolating the
8-Fermion
Minimal
Solutions
(Model 4 and
Model 5)

$1 \times \{-5\} + 1 \times \{9\} + 1 \times \{13\} + 1 \times \{-17\} + 1 \times \{18\} + 2 \times \{-22\} + 1 \times \{26\}$	$1 \times \{4\}$
$1 \times \{-9\} + 1 \times \{11\} + 1 \times \{13\} + 1 \times \{-15\} + 1 \times \{22\} + 2 \times \{-24\} + 1 \times \{26\}$	$1 \times \{2\}$
$1 \times \{-5\} + 1 \times \{-6\} + 1 \times \{-10\} + 1 \times \{-16\} + 2 \times \{21\} + 1 \times \{27\} + 1 \times \{-32\}$	$1 \times \{11\}$
$1 \times \{5\} + 1 \times \{7\} + 1 \times \{10\} + 1 \times \{17\} + 2 \times \{-22\} + 1 \times \{-29\} + 1 \times \{34\}$	$1 \times \{12\}$
$1 \times \{-7\} + 1 \times \{11\} + 1 \times \{15\} + 1 \times \{-19\} + 1 \times \{22\} + 2 \times \{-26\} + 1 \times \{30\}$	$1 \times \{4\}$
$1 \times \{-11\} + 1 \times \{13\} + 1 \times \{15\} + 1 \times \{-17\} + 1 \times \{26\} + 2 \times \{-28\} + 1 \times \{30\}$	$1 \times \{2\}$
$1 \times \{-5\} + 1 \times \{11\} + 1 \times \{17\} + 1 \times \{22\} + 1 \times \{-23\} + 2 \times \{-28\} + 1 \times \{34\}$	$1 \times \{6\}$
$1 \times \{-9\} + 1 \times \{13\} + 1 \times \{17\} + 1 \times \{-21\} + 1 \times \{26\} + 2 \times \{-30\} + 1 \times \{34\}$	$1 \times \{4\}$

Findings

The Rejections

- ✗ Models with 6 or 7 fermions require ≥ 2 Higgs fields.
- ✗ Models 2, 3, 6, 8, 11... lack residual symmetries to stabilize DM.
- ✗ Models 7, 9, 10, 12... require >3 scalar multiplets for the Scotogenic realization.

The Benchmark Selection



We extract Model 4 (Solution-A) and Model 5 (Solution-B).

These represent the absolute minimal 8-fermion states with minimal scalar sectors that perfectly retain stabilizing residual symmetries.

$$U(1)_D \xrightarrow{\langle \eta \rangle} \mathbb{Z}_N$$

Solution-A (Model 4)
η charge = 2 Remnant Symmetry = $\mathbb{Z}_2$ Result: Perfectly stabilizes a multi-component dark sector.

Solution-B (Model 5)
η charge = 4 Remnant Symmetry = $\mathbb{Z}_4$

Benchmark model

Anomaly-free charge assignments (multiplicity $\times$ charge)

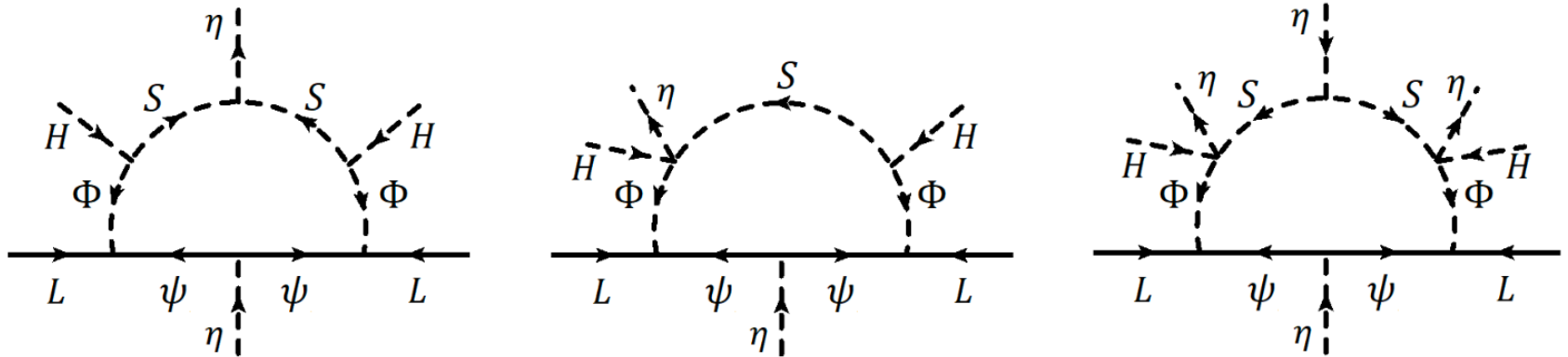
Solution A: $2 \times \{1\} + 2 \times \{-4\} + 1 \times \{2\} + 1 \times \{3\} + 1 \times \{-5\} + 1 \times \{6\}$

The Yukawa Lagrangian:

$$-\mathcal{L}_Y \supset y_{i\alpha} \bar{L}_i \tilde{\Phi} \Psi_{\alpha}^{(1)} + \frac{f_{\alpha\beta}}{2} \Psi_{\alpha}^{c(1)} \Psi_{\beta}^{(1)} \eta^* \\ + f' \Psi^{c(2)} \Psi_1^{(-4)} \eta + \dots$$

- **Blue terms:** $\Psi^{(1)}$ generate two massive Majorana fermions (N_1, N_2)
- **Red terms:** $\Psi^{(2)}, \Psi^{(-4)}$ generate Massive Dirac Fermions (ξ, ζ_1, ζ_2)
- **Green target:** Φ and S interactions define the Scalar Portal

m_ν generation



Representative Feynman diagrams for 1-loop m_ν mass

- 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 $\rightarrow$ lightest neutrino mass is essentially massless (higher order loop corrections inducing a very tiny mass)

The Blueprint of Solution A: Scalar Multiplets

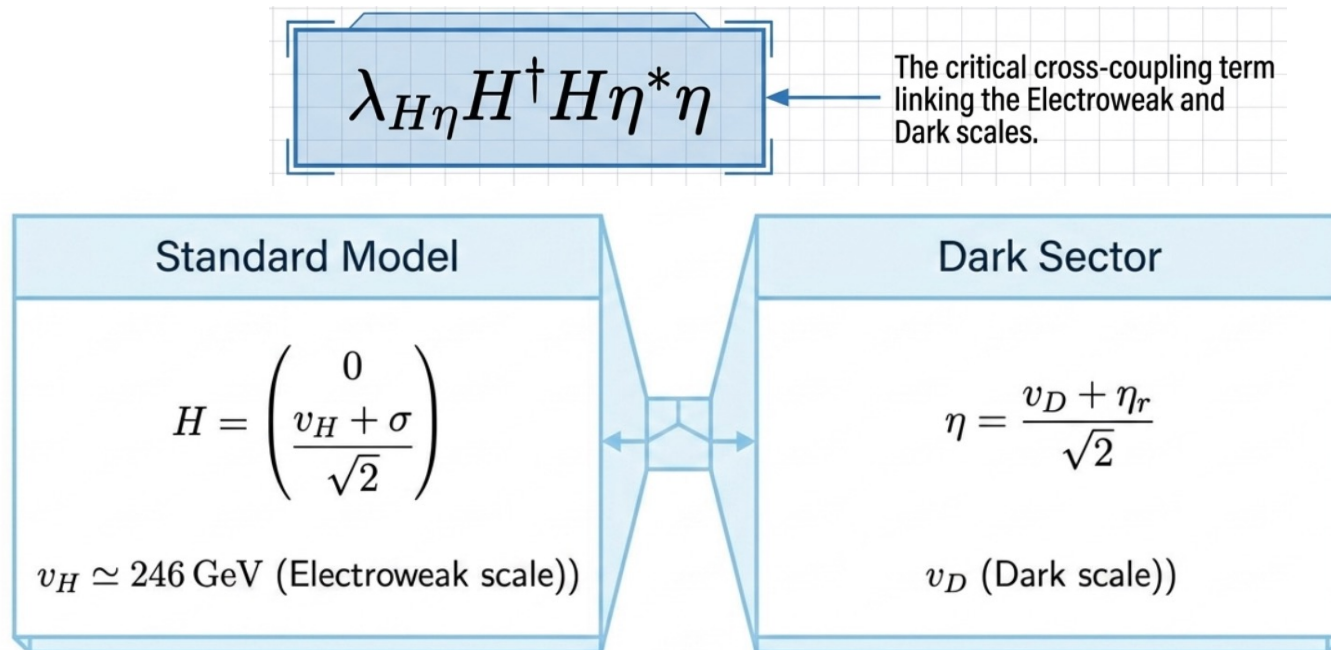
		$SU(2)_L \times U(1)_Y \times U(1)_D$
1	The Breaker:	$\eta \rightarrow (1, 0, 2)$
2	The Singlet:	$S \rightarrow (1, 0, 1)$
3	The Doublet:	$\Phi = (\phi^+, \phi^0)^T \rightarrow (2, 1/2, -1)$

These assignments guarantee that a single scalar field (η) can break the symmetry and dynamically generate masses for the entire dark sector.

Scalar potential

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

To generate m_ν non-zero mixing between Φ and S is needed $\rightarrow$ Scalar DM is singlet-doublet admixture



Masses and mixings

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

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

- For mixing between $\text{Re}(\phi^0)$ and $\text{Re}(S)$ with mass eigen states H_1 and H_2 :

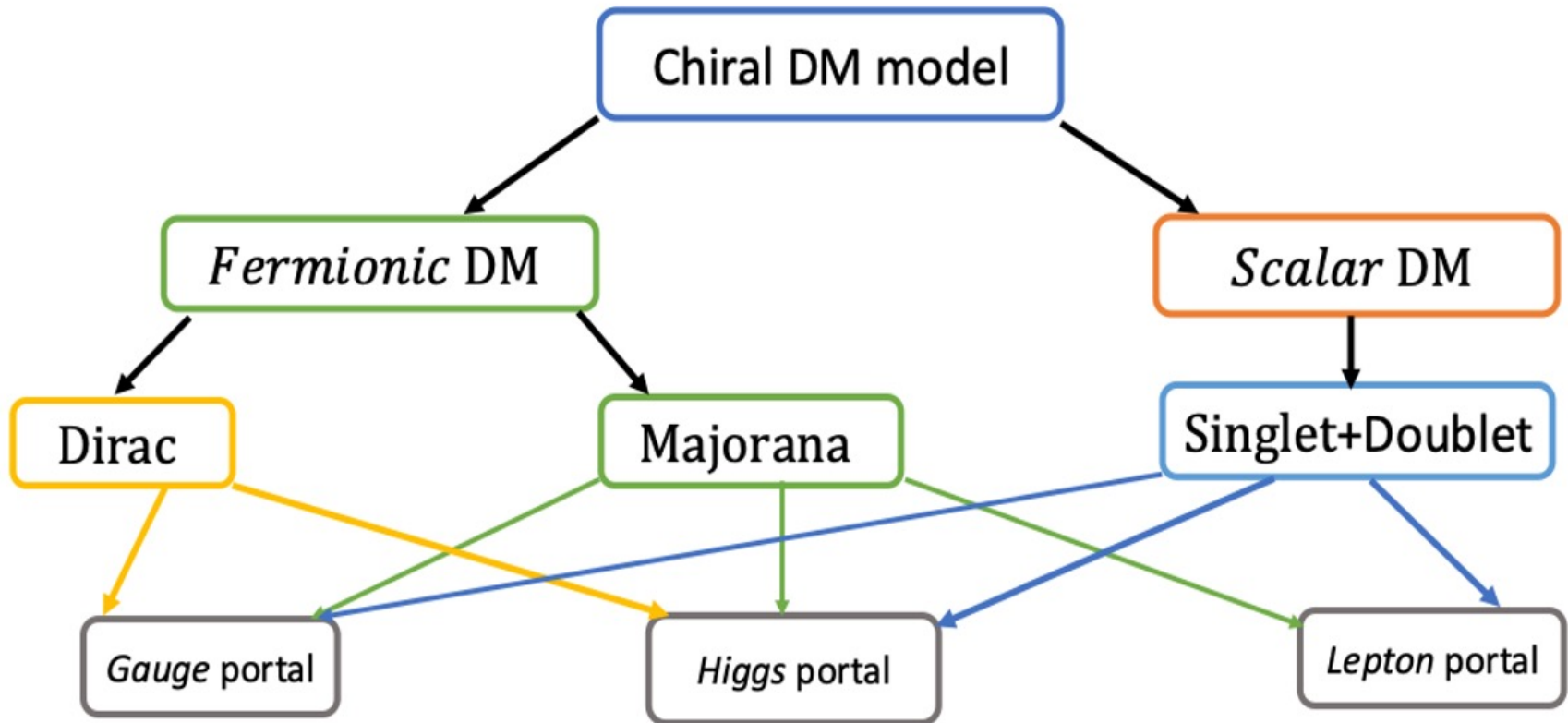
$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \text{Re}(\phi^0) \\ \text{Re}(S) \end{pmatrix}, \quad \sin 2\alpha = \frac{\sqrt{2}\mu_{S\Phi} v_H}{m_{H_2}^2 - m_{H_1}^2}.$$

- For mixing between $\text{Im}(\phi^0)$ and $\text{Im}(S)$ with mass eigen states A_1 and A_2 :

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

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

All possible *DM* candidates in this scenario..



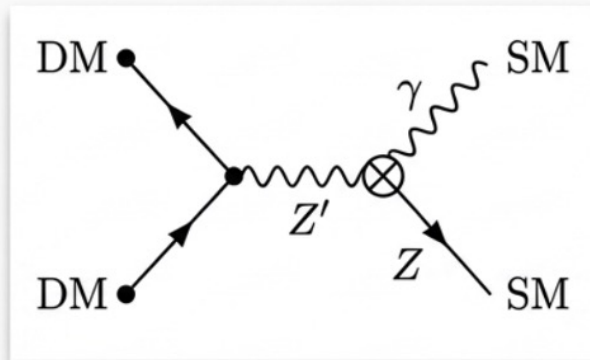
Fermionic *DM* is less explored in Scotogenic scenarios!

Fermion *DM* pheno (gauge portal)

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

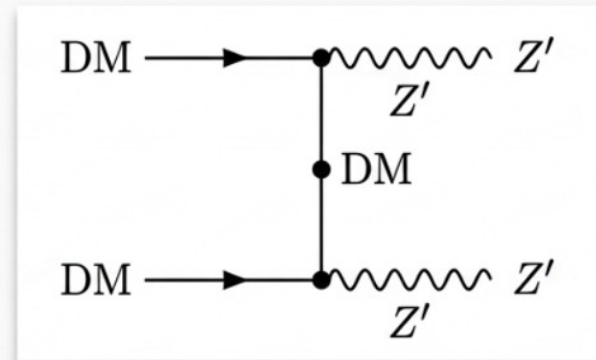
- *DM* coupling with gauge boson Z' leads to dominant annihilation modes
- When $m_{DM} > m_{Z'}$ dominant annihilation channel is $DM DM \rightarrow Z' Z'$

Majorana DM



Annihilation is strictly p -wave suppressed due to axial-vector coupling.

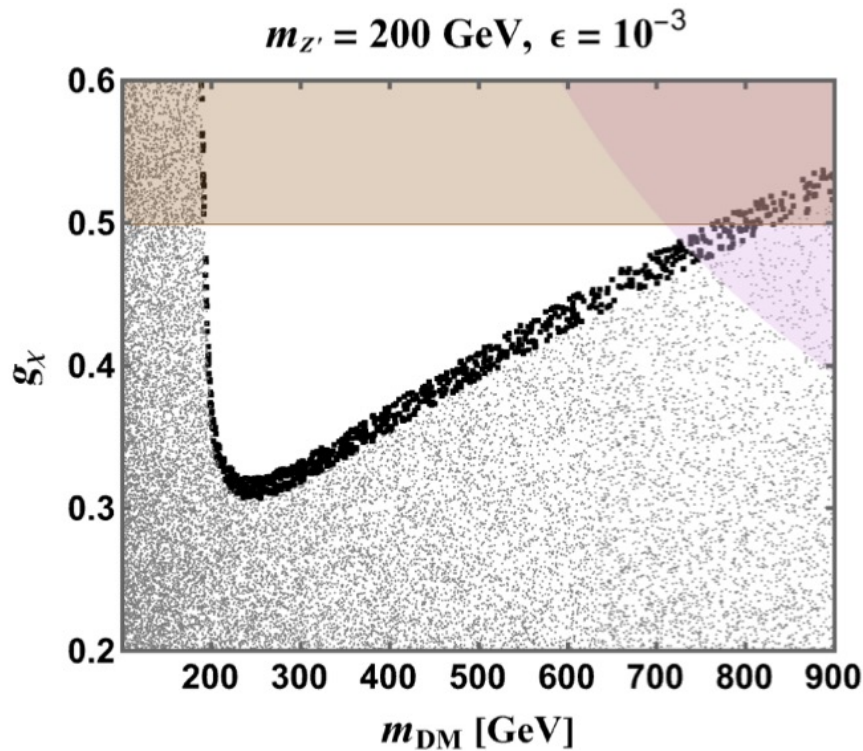
Dirac DM



Annihilation proceeds unsuppressed via s -wave.

DD constraints are easily bypassed due to lack of vectorial coupling

Fermion DM phenomenology (gauge portal)



Majorana DM

Dirac DM

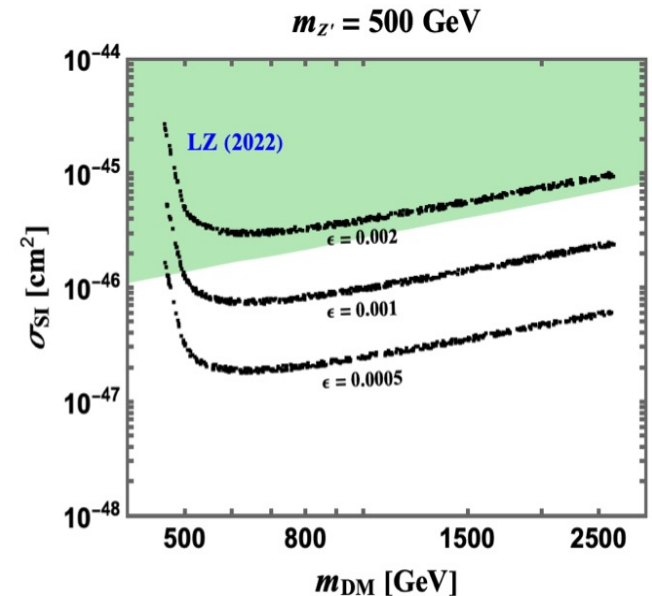
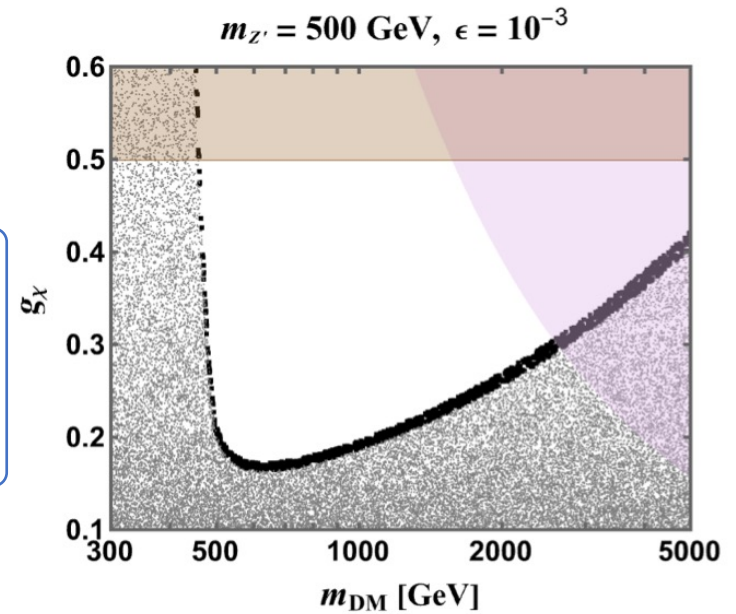


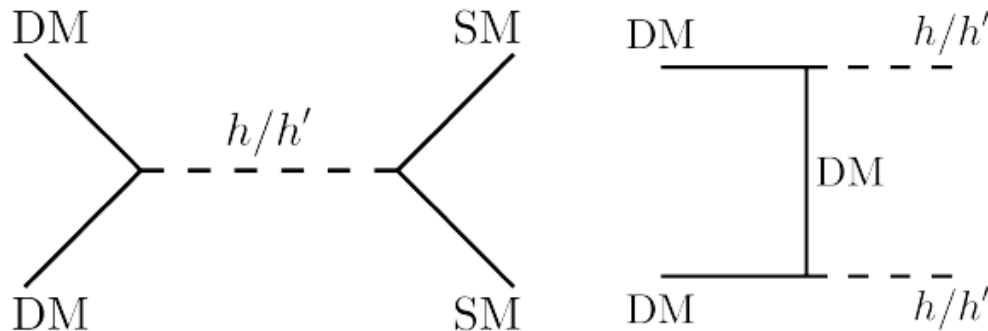
Fig: Parameter space in gauge coupling (g_χ) vs. m_{DM} plane with black points showing $\Omega h^2 = 0.12$. Grey data points excluded from DM overabundance. Brown (pink)-region excluded by perturbativity bound on gauge (Yukawa) coupling. Corr Dirac DM plot is shown in R.

R: Corr Direct Detection plot is shown. Since $\sigma \propto \epsilon^2$, gauge kinetic mixing ϵ is small to satisfy DD constraints

Fermionic *DM* pheno (Scalar portal)

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

- Small gauge coupling, opening up the Higgs portal channels
- *DM* coupling with neutral scalars h, h' lead to dominant annihilation modes



- S-channel annihilation modes are particularly important when $m_{DM} \sim m_{h/h'}/2$
- When $m_{DM} > m_{h,h'}$, *DM* pair annihilate into $h h, h h',$ and $h' h'$
- *DM* coupling with h is suppressed by $\sin\theta$, dom annihilation channel $DM DM \rightarrow h' h'$
- In this region *DM* is identified as secluded *DM* $\rightarrow$ limits from *DD* are weak
- LFV safe! Yukawas entering LFV process distinct than Yukawas needed here to satisfy bounds applicable in fermionic *DM* sector

Fermionic *DM* pheno (Majorana)

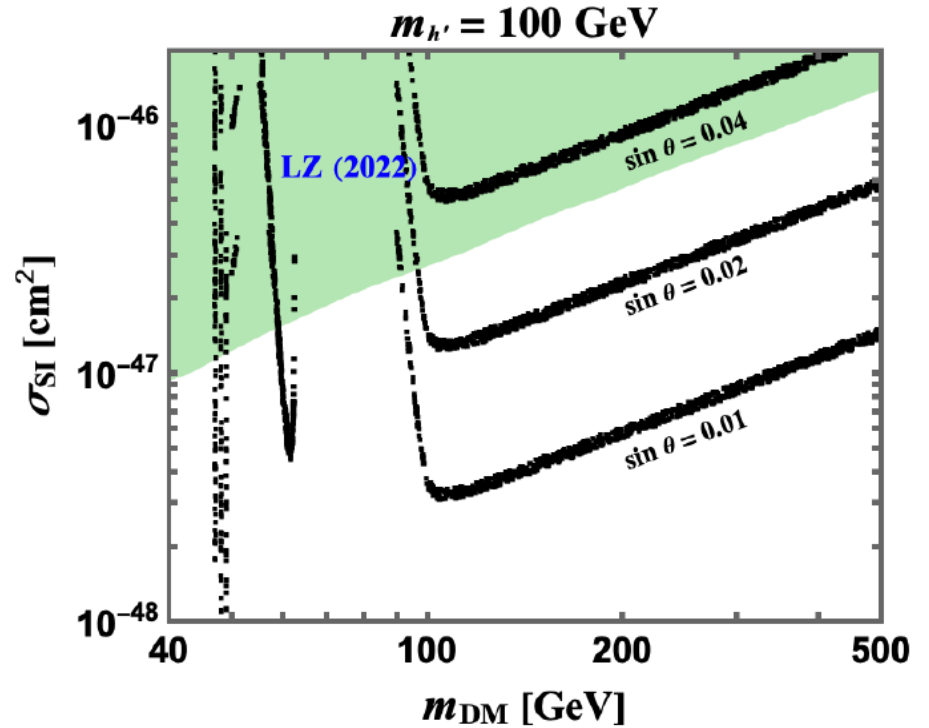
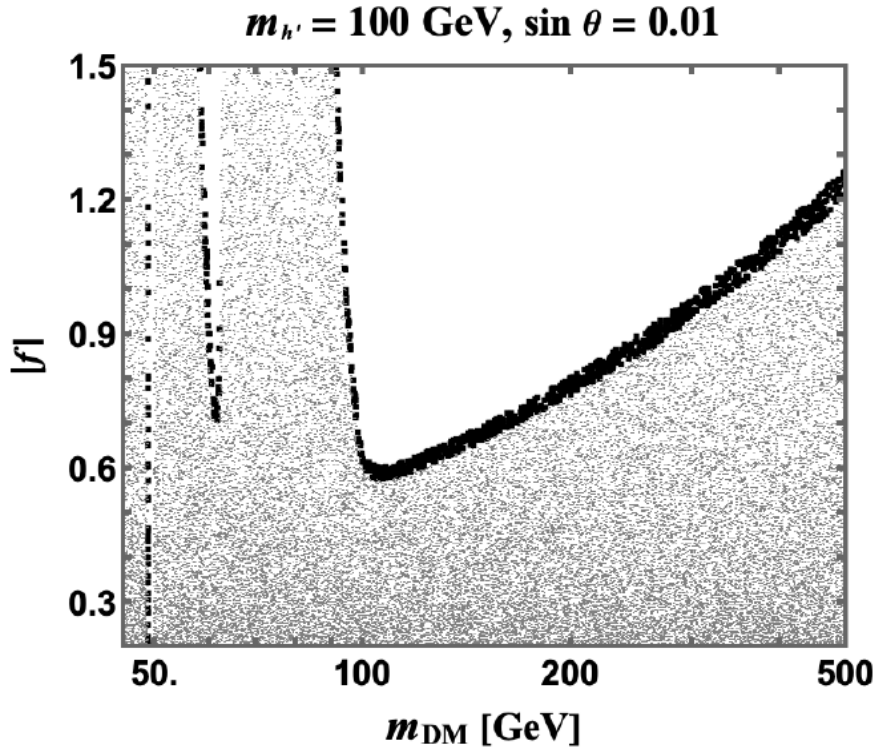


Fig L: Parameter space in Yukawa coupling (f) vs. m_{DM} plane consistent with relic density constraint for **Majorana DM**

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

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

Low Mass Fermionic DM pheno

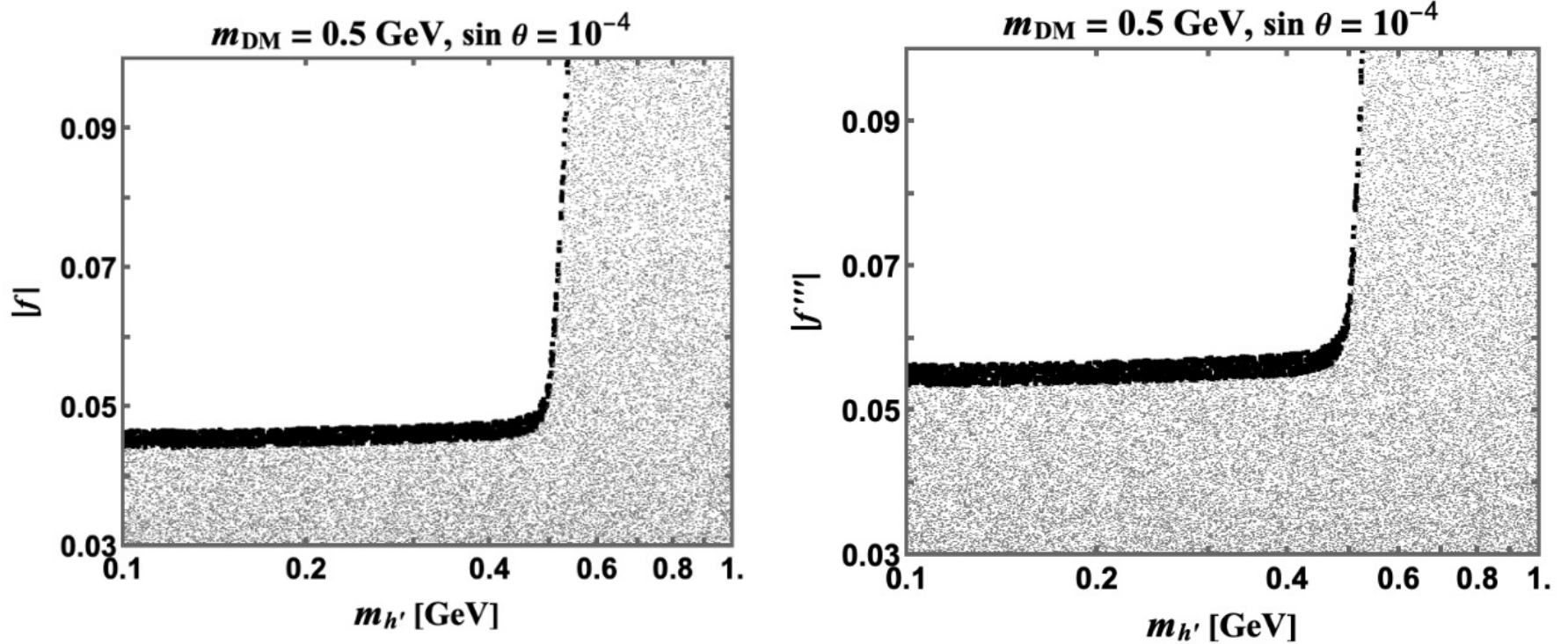
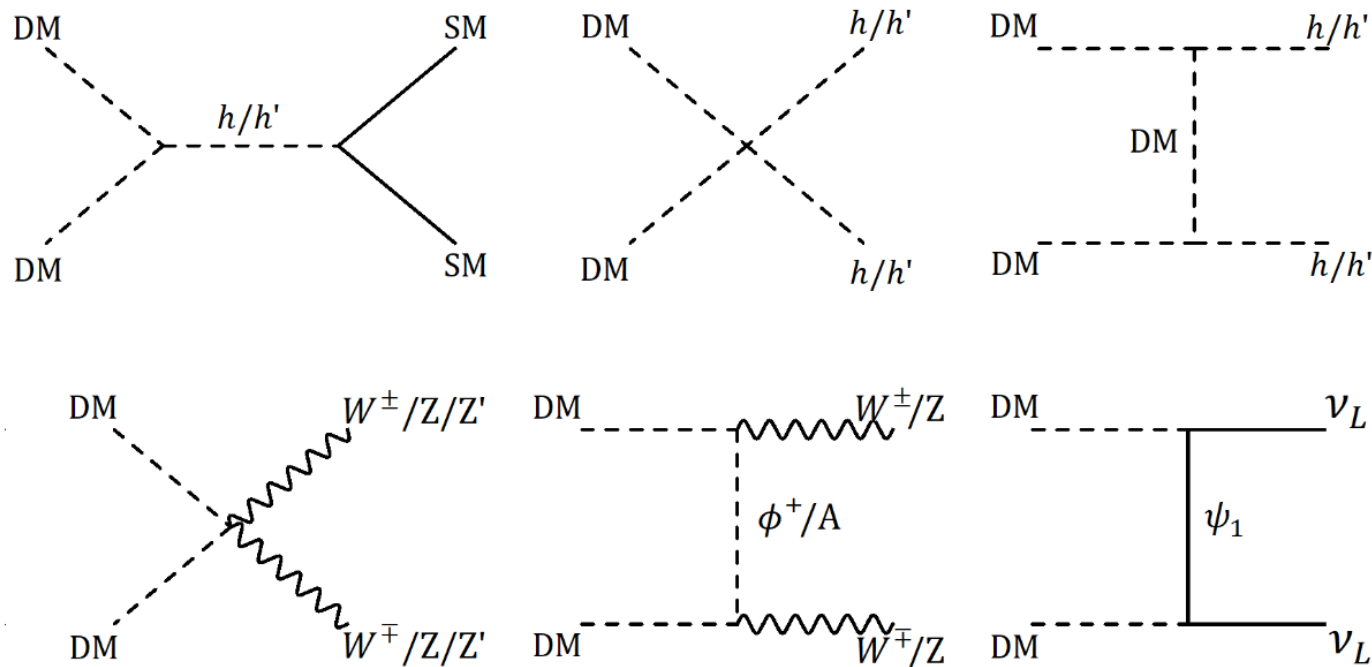


Fig: Parameter space in Yukawa coupling (f, f''') vs. scalar mass ($m_{h'}$) with relic density constraints for **Majorana** (L) and **Dirac** (R) DM for **low mass region** (500 MeV). DM primarily annihilates into $h' h'$, avoiding stringent CMB constraints, meson decay constraints are safe for $\sin \theta \sim 10^{-4}$

Scalar *DM* pheno

- To generate m_ν need mixing between scalar doublet ϕ and singlet scalar S
- Lightest neutral state among $\{H_1, H_2, A_1, A_2\}$: 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 pheno

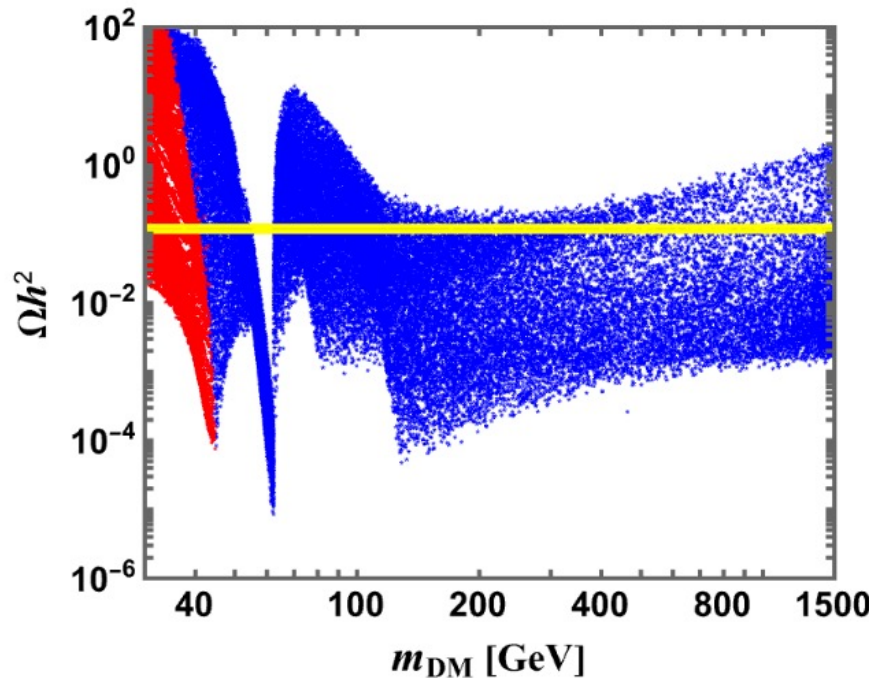


Fig: Relic density of DM as a function of m_{DM}
red (blue)-colored data points are excluded (allowed) by constraints from Z-decay width measurements and yellow-shaded region indicates Planck relic density constraints

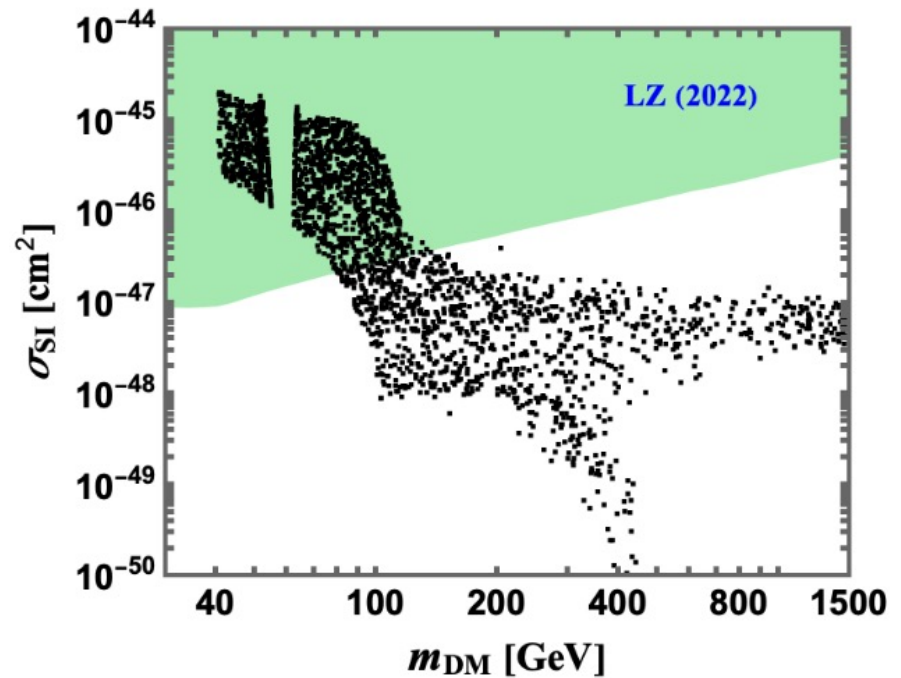


Fig: DM -nucleon spin independent cross section for $\sin \alpha = 0.99$. The green-shaded region denotes the excluded parameter space by LZ

DM Taxonomy

DM Candidate	Dominant Portal	Kinematics (s-wave/p-wave)	Direct Detection Profile
Majorana Fermion (N_1)	Gauge (Z') or Higgs (h/h')	p -wave suppressed (axial-vector Z' coupling)	Weak (No vectorial coupling to nucleons)
Dirac Fermion (ξ, ζ)	Gauge (Z')	s -wave (vectorial coupling allowed)	Highly constrained by kinetic mixing (ϵ)
Scalar (H_1)	Singlet-Doublet Mixing	s -wave / resonance dominant	Bounded by Higgs mixing angle $\sin \theta$

Takeaways

Theoretical Elegance

- Originates from an anomaly-free $SU(3) \times SU(2)$ non-Abelian progenitor.
- Chiral gauge structure organically protects fermion mass scales without extreme fine-tuning.

Intrinsic Stability

- $U(1)_D$ spontaneous symmetry breaking topologically guarantees remnant Z_2 or Z_4 symmetries.
- Dark matter stability requires no ad hoc assumptions.

Testable Predictions

- Scotogenic 1-loop mechanism strictly predicts exactly one massless light neutrino.
- Diverse DM candidates yield distinct kinematic signatures, actively probed by LZ and future direct detection experiments.

Thank you