The Scotos (*dark*) side of Neutrinos

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DM and ν origin story

Origin of neutrino mass and dark matter are two pressing puzzles in *PPC* $\rightarrow$ can be addressed by hidden sector containing new particles/symmetries

Radiative connection: long history of radiative m_ν generation $\rightarrow$ are DM and m_ν 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 and take advantage of that connection between DM-ν to probe nature of m_ν

The Dark side 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 ν sector symmetries (Lepton symmetries) i.e mixing patterns and/or lepton number

The Scotogenic model

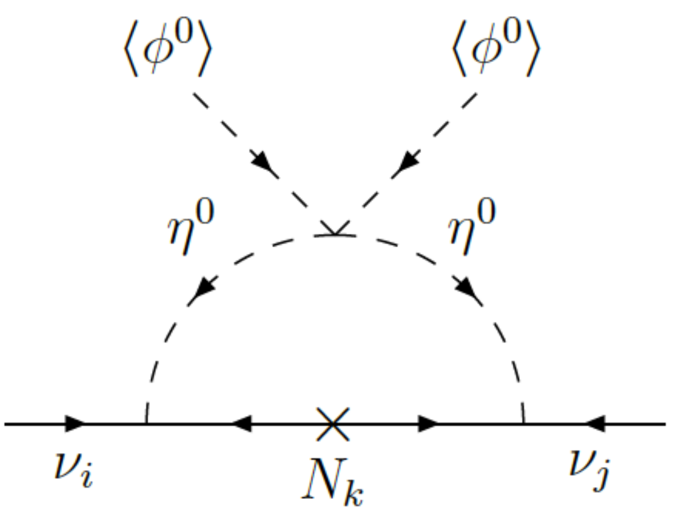
Scotogenic Model = SM + 3 singlet Fermions ($N_{1,2,3}$) + scalar doublet (η) + dark Z_2

[Ma, hep-ph/0601225]

Dubbed the scotogenic model, from Greek word 'scotos' meaning darkness, this '06 proposal explains the smallness of m_ν via a loop-generated mass where DM plays a central role in completing the loop

- 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 generates

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



Challenges, goals and current framework

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

DM stability is arising from gauge symmetry
Protect *DM* mass down to GeV-TeV scale
Achieved by breaking the dark gauge symmetry around GeV-TeV scale

Anomaly-free solutions to SM with dark *U(1)* gauge symmetry
Scotogenic neutrino mass: *LLHH* operator arise through loops
Explore different *DM* phenomenology scenarios: (scalar *DM* (singlet-doublet mixture), Majorana/Dirac Fermion *DM*)

Anomaly free solutions with min chiral fields

- Hidden sector containing *N* SM-singlet chiral fermions $\chi(n_i)$ with nonzero $U(1)_D$ charges n_i ($i = 1, ..., N$)
- All *SM* fields are neutral under $U(1)_D$
- Cancellation of gauge anomaly and mixed gauge-gravitational anomaly imposes the following constraints (Diophantine equations) on charge assignments

$$\sum_{i=1}^{N} n_i = 0$$

$$\sum_{i=1}^{N} n_i^3 = 0$$

Find optimum number of chiral fields (maximal charge ratio 6) + minimal scalar sector to obtain suitable Scotogenic solutions

Solutions with $N \leq 8$ fields

Model	Chiral Fermions: Multiplicity*(Charge)	Minimal Higgs Sector: (Charge)
1	3*(1)+2*(-4)+1*(5)	
2	1*(1)+1*(-2)+1*(-3)+2*(5)+1*(-6)	
3	1*(-1)+2*(-2)+3*(3)+1*(-4)	
4	2*(1)+1*(2)+1*(3)+2*(-4)+1*(-5)+1*(6)	(2)
5	1*(-1)+3*(-2)+1*(3)+1*(5)+1*(6)+1*(-7)	(4)
6	2*(-1)+1*(-2)+1*(3)+1*(-4)+1*(6)+1*(7)+1*(-8)	(5)
7	1*(-1)+2*(-2)+1*(-4)+2*(5)+1*(7)+1*(-8)	(3)
8	1*(1)+1*(2)+2*(3)+1*(-4)+1*(-6)+1*(-8)+1*(9)	(5)
9	1*(2)+1*(-3)+1*(-4)+1*(5)+1*(-6)+2*(7)+1*(-8)	(1)
10	1*(1)+1*(2)+1*(3)+1*(5)+2*(-6)+1*(-9)+1*(10)	(4)
11	1*(-1)+1*(-2)+1*(-4)+1*(-5)+2*(7)+1*(8)+1*(-10)	(3)
12	1*(-1)+1*(-2)+2*(-4)+1*(5)+1*(7)+1*(10)+1*(-11)	(6)
13	2*(1)+1*(3)+1*(-4)+1*(6)+1*(-8)+1*(-10)+1*(11)	(7)
14	1*(-1)+1*(3)+1*(5)+1*(6)+1*(-7)+2*(-8)+1*(10)	(2)
15	1*(-2)+2*(-3)+1*(-4)+1*(5)+1*(9)+1*(10)+1*(-12)	(7)
16	1*(3)+1*(-4)+1*(-5)+1*(6)+1*(-8)+2*(9)+1*(-10)	(1)
17	1*(-1)+1*(-2)+1*(-4)+1*(-6)+2*(7)+1*(11)+1*(-12)	(5)
18	2*(-2)+1*(-3)+1*(5)+1*(-6)+1*(10)+1*(11)+1*(-13)	(8)
19	1*(1)+1*(2)+2*(5)+1*(-6)+1*(-8)+1*(-12)+1*(13)	(7)
20	2*(-1)+1*(-4)+1*(5)+1*(-8)+1*(10)+1*(13)+1*(-14)	(9)
21	1*(1)+1*(2)+1*(5)+1*(7)+2*(-8)+1*(-13)+1*(14)	(6)
22	1*(-2)+1*(-3)+1*(-4)+1*(-7)+2*(9)+1*(12)+1*(-14)	(5)
23	1*(1)+1*(3)+1*(6)+1*(7)+2*(-10)+1*(-11)+1*(14)	(4)
24	1*(-1)+1*(-2)+2*(-6)+1*(7)+1*(9)+1*(14)+1*(-15)	(8)
25	1*(4)+1*(-5)+1*(-6)+1*(7)+1*(-10)+2*(11)+1*(-12)	(1)
26	1*(1)+1*(-4)+1*(-7)+1*(-8)+1*(10)+2*(11)+1*(-14)	(3)
27	1*(-2)+1*(-4)+2*(-5)+1*(7)+1*(11)+1*(14)+1*(-16)	(9)
28	1*(-1)+1*(-2)+1*(-6)+1*(-8)+2*(9)+1*(15)+1*(-16)	(7)
29	1*(-3)+1*(5)+1*(7)+1*(-9)+1*(10)+2*(-12)+1*(14)	(2)
30	1*(-3)+2*(-4)+1*(-6)+1*(7)+1*(13)+1*(14)+1*(-17)	(10)

Table 1: $U(1)_D \subset SU(3) \times SU(2)$

Representative model

Anomaly-free charge assignments (multiplicity*(charge))

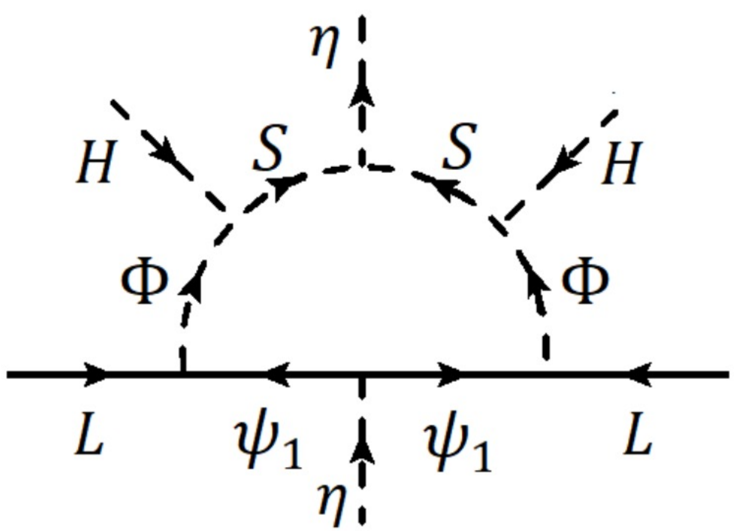
Model : 2 × {1} + 2 × {−4} + 1 × {2} + 1 × {3} + 1 × {−5} + 1 × {6}

Two Weyl fermions with $U(1)_D$ charges 1 and −4, one state each with charge 2, 3, −5 and 6

Minimally extended Higgs sector:

scalar singlet field η (1, 0, 2), singlet S (1, 0, 1), doublets H (2, ½, 0) and $\Phi(2, \frac{1}{2}, 1)$

Topology for 1 loop generation of m_ν

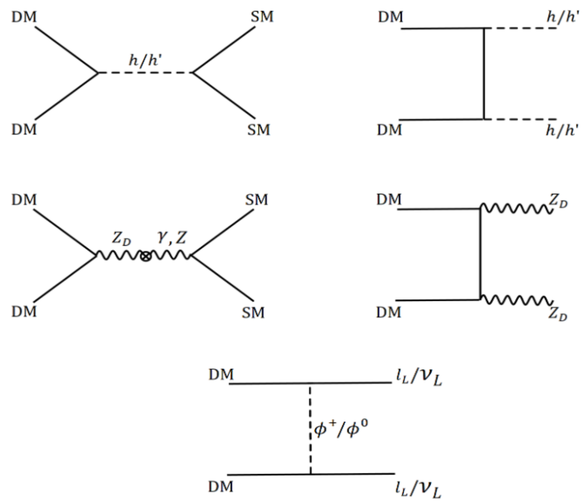


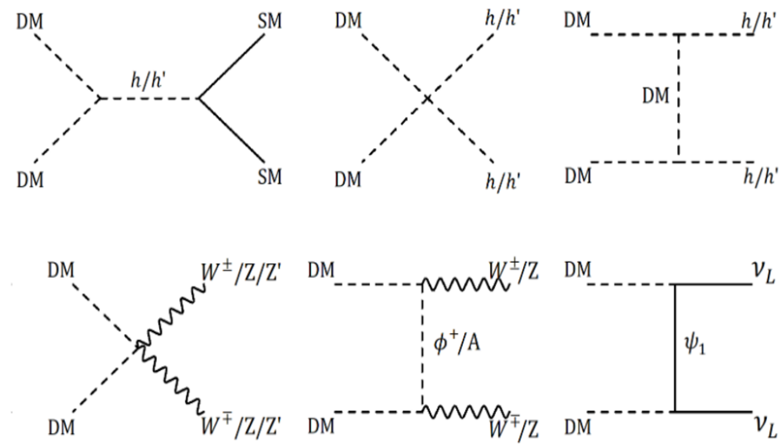
Lightest field inside the loop could be DM

Dark Matter

U(1)$_D$ gauge symmetry broken down to discrete Z_2 ensuring the stability of *DM*

I) Fermionic *DM* (Dirac and Majorana) II) Scalar *DM* of singlet-doublet mixture





Ref: Relevant Feynman diagrams that contribute to the annihilation of the Fermion DM (L) and Scalar DM (R)

Fermionic *DM* phenomenology(Majorana)

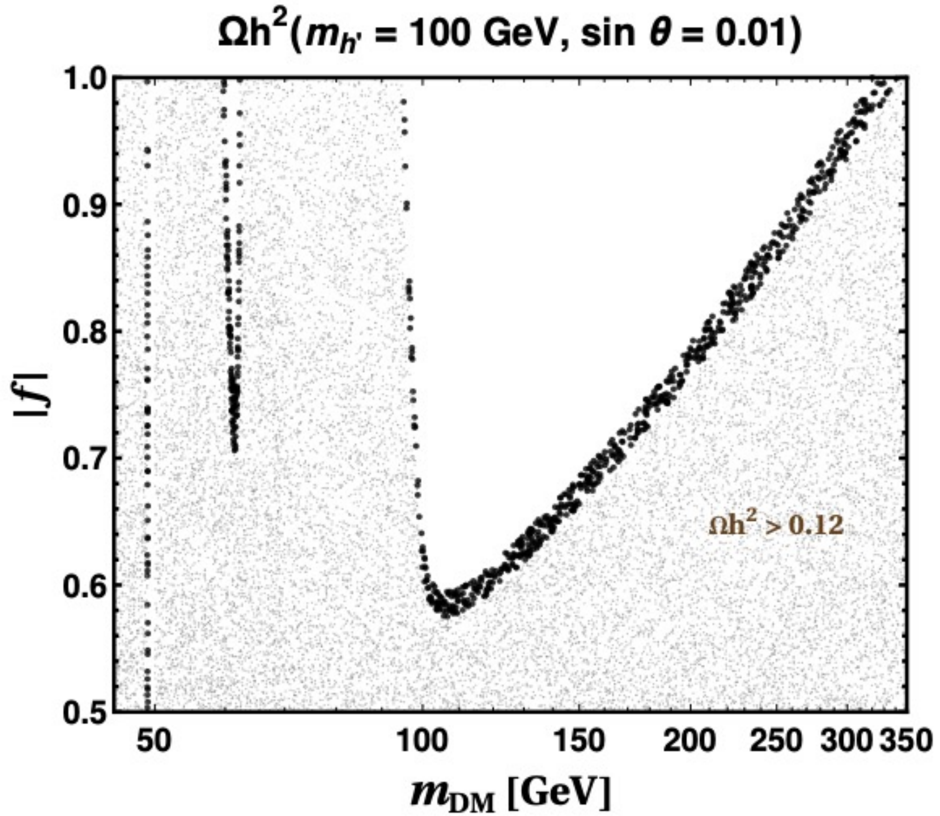


Fig: Parameter space in Yukawa coupling (f) vs. m_{DM} plane consistent with Planck constraint for Majorana *DM*

LFV safety
Yukawas entering LFV process are distinct from yukawas needed here to satisfy DM bounds

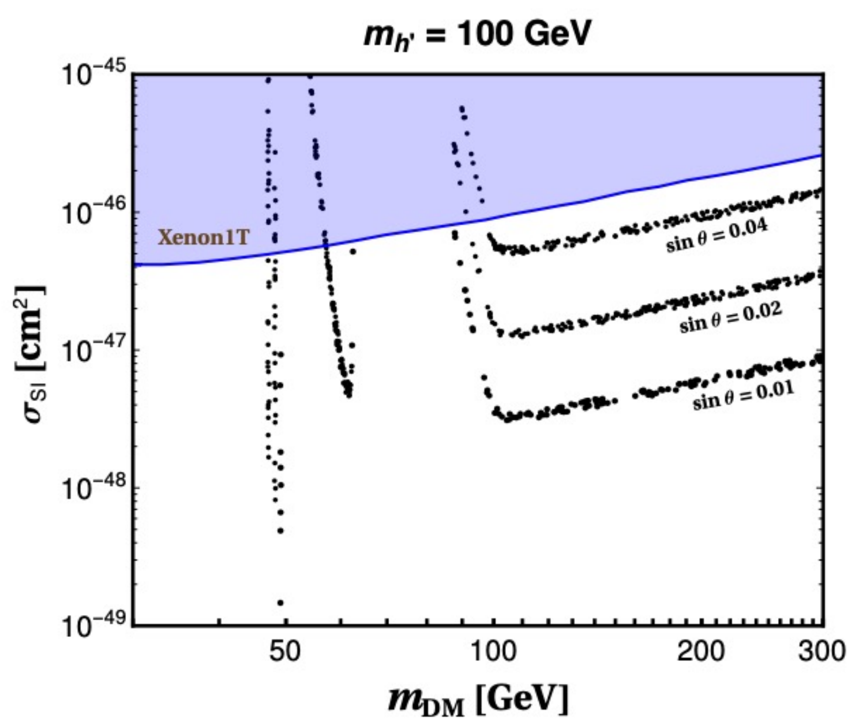


Fig: Spin independent cross section vs. m_{DM} consistent with DD constraints for Majorana *DM*

Fermion *DM* phenomenology (Dirac)

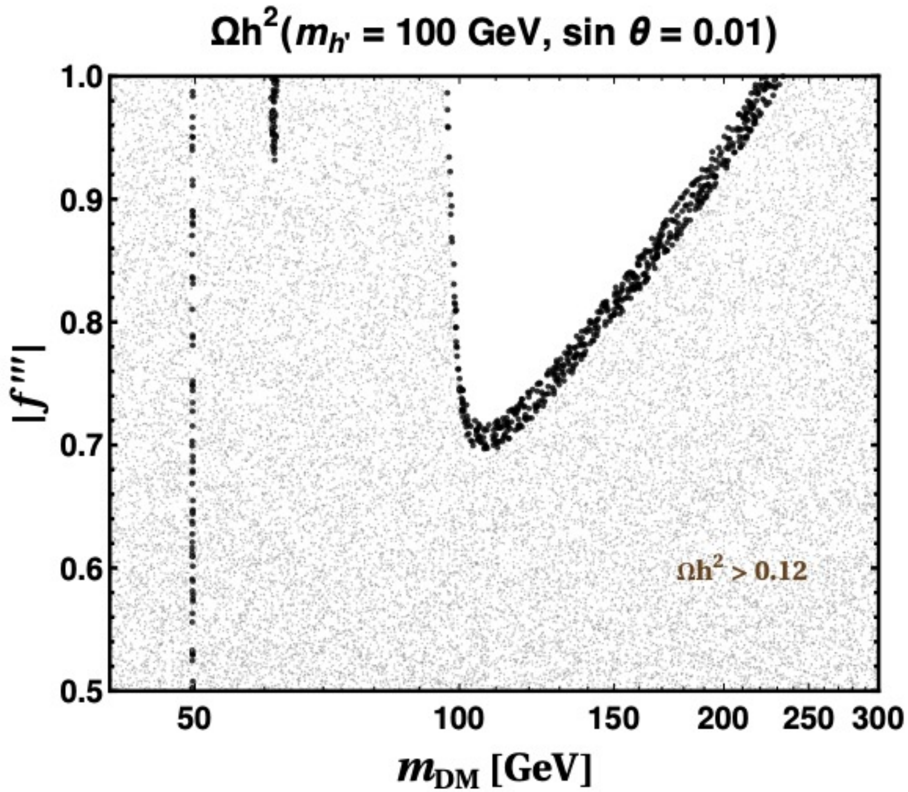


Fig: Parameter space in Yukawa coupling (f''') vs. m_{DM} plane consistent with Planck constraint for Dirac *DM*

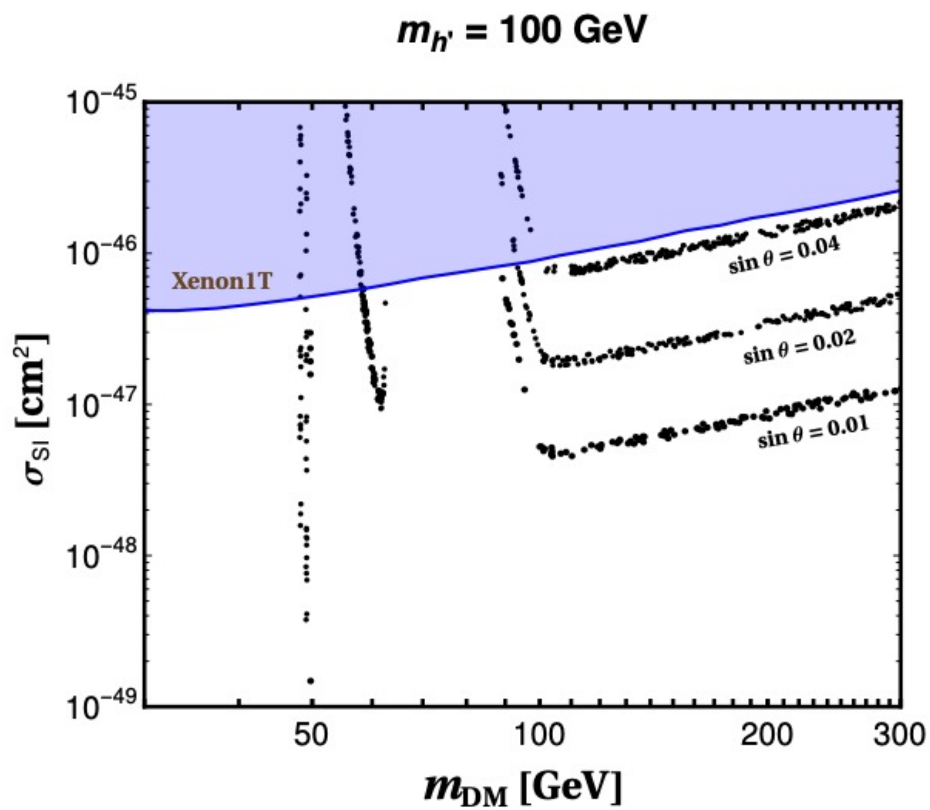
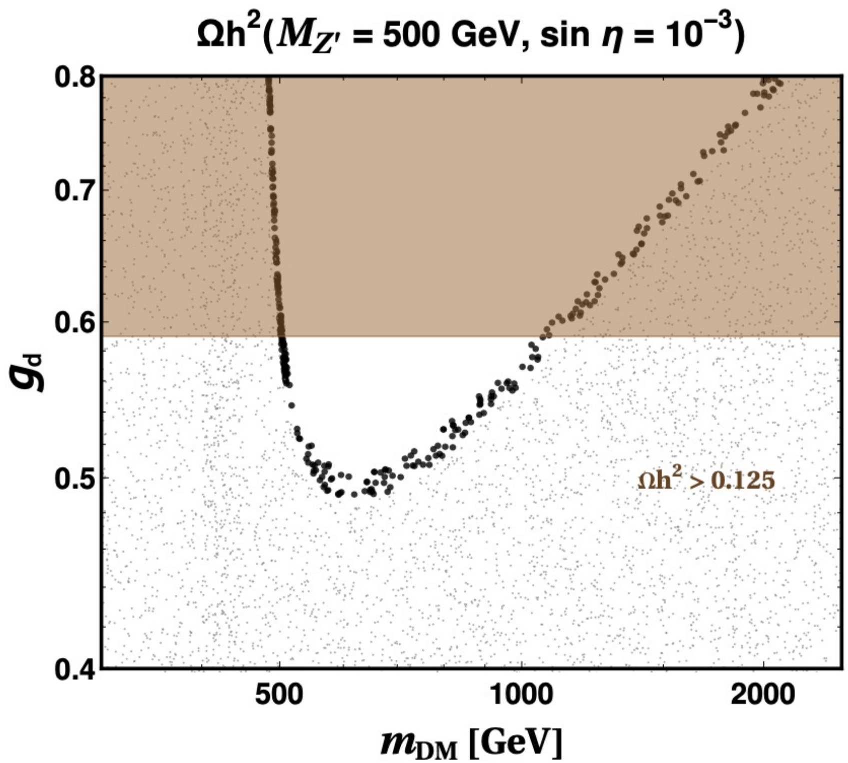
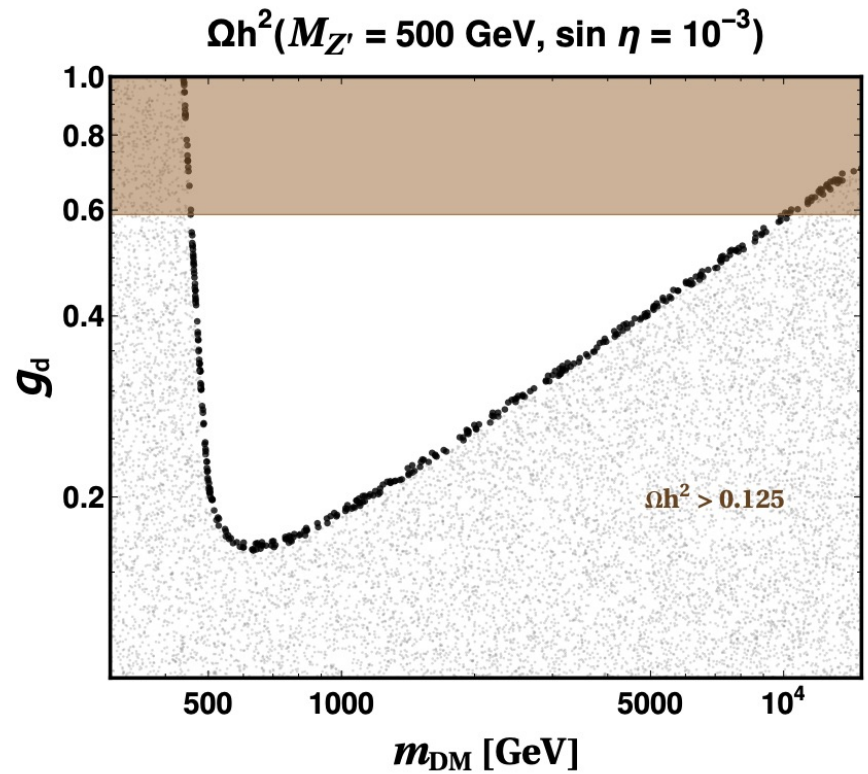


Fig: Spin independent cross section vs. m_{DM} consistent with DD constraints for Dirac *DM*

Fermion *DM* phenomenology (gauge portal)



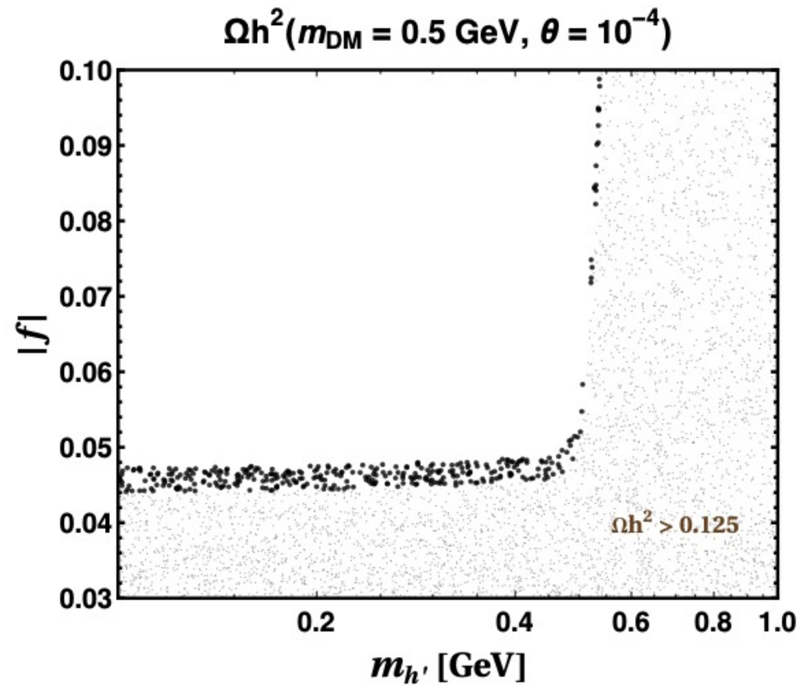


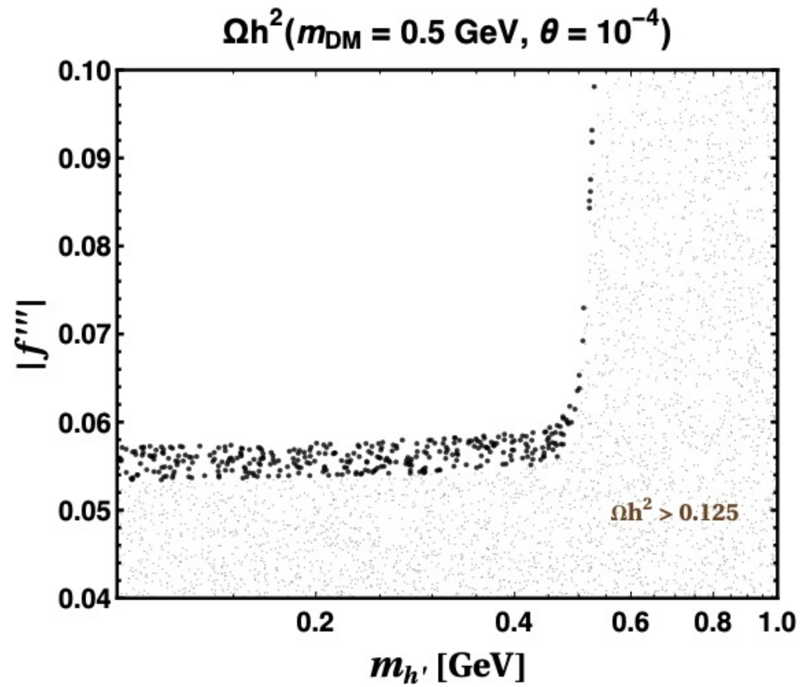
Majorana DM

Dirac DM

Fig: Parameter space in gauge coupling (g_d) vs. m_{DM} plane consistent with DM relic density constraint. $m_{H'}$ is 2.1× m_{DM} and $sin\eta$ represents kinetic mixing

Fermionic *DM* phenomenology (low mass)





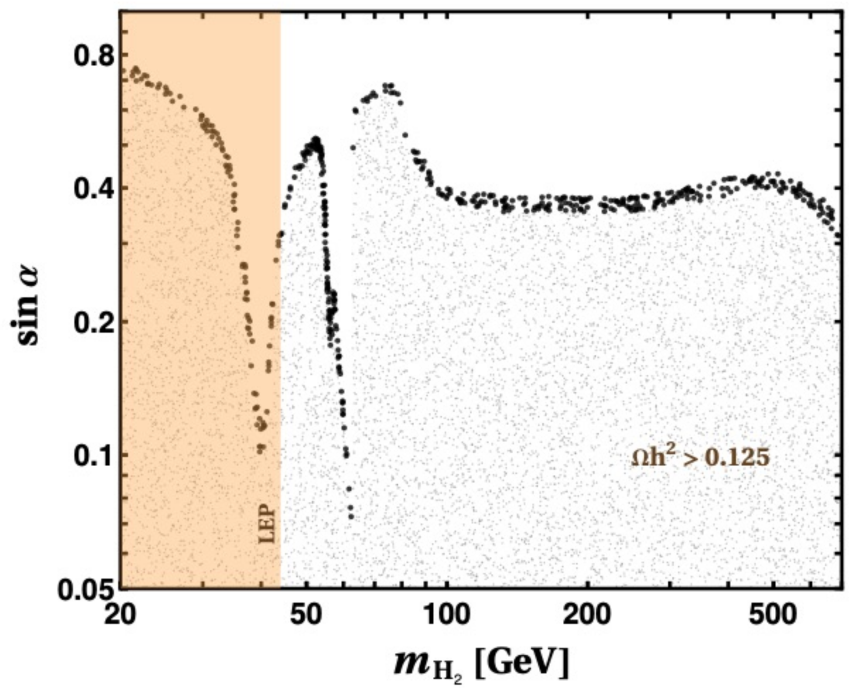
Majorana DM

Dirac DM

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

Scalar *DM* phenomenology

Scalar *DM* consists of singlet-doublet mixture



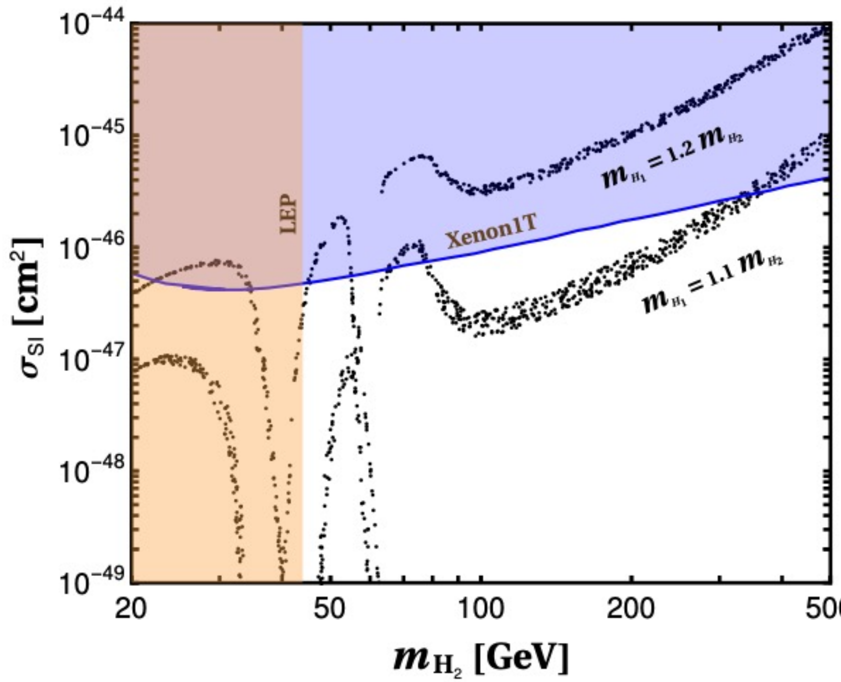


Fig (L): Parameter space in mixing angle sin α (mixing for CP even scalar fields H_1 and H_2) vs. m_{DM} plane for m_{H1}=1.1 (1.2)×M_{DM} consistent with Planck constraint for scalar *DM.*
Fig (R): *Spin independent* cross section vs. m_{DM} consistent with LEP bound and Xenon1T bound

Summary

Present complete set of relevant anomaly-free solutions with add^n of $U(1)_D$ chiral fermions with minimalized scalar sector to address *DM and* m_ν

Model of the dark sector includes m_ν and *DM* originating from Scotogenic mechanism

DM stability is protected by the residual of *U(1)*$_D$ symmetry with the scalar singlet η generating masses to the all dark fermions

DM phenomenology explored for both fermionic type (Majorana and Dirac) and scalar type (singlet-doublet) with DM masses ranging from 100 MeV to TeV scale

Thank you!
Questions?