Dark side of the seesaw

Ivo de Medeiros Varzielas

CFTP, Instituto Superior Técnico, Universidade de Lisboa

Workshop on Multi-Higgs Models, Lisbon, 2018/09/07

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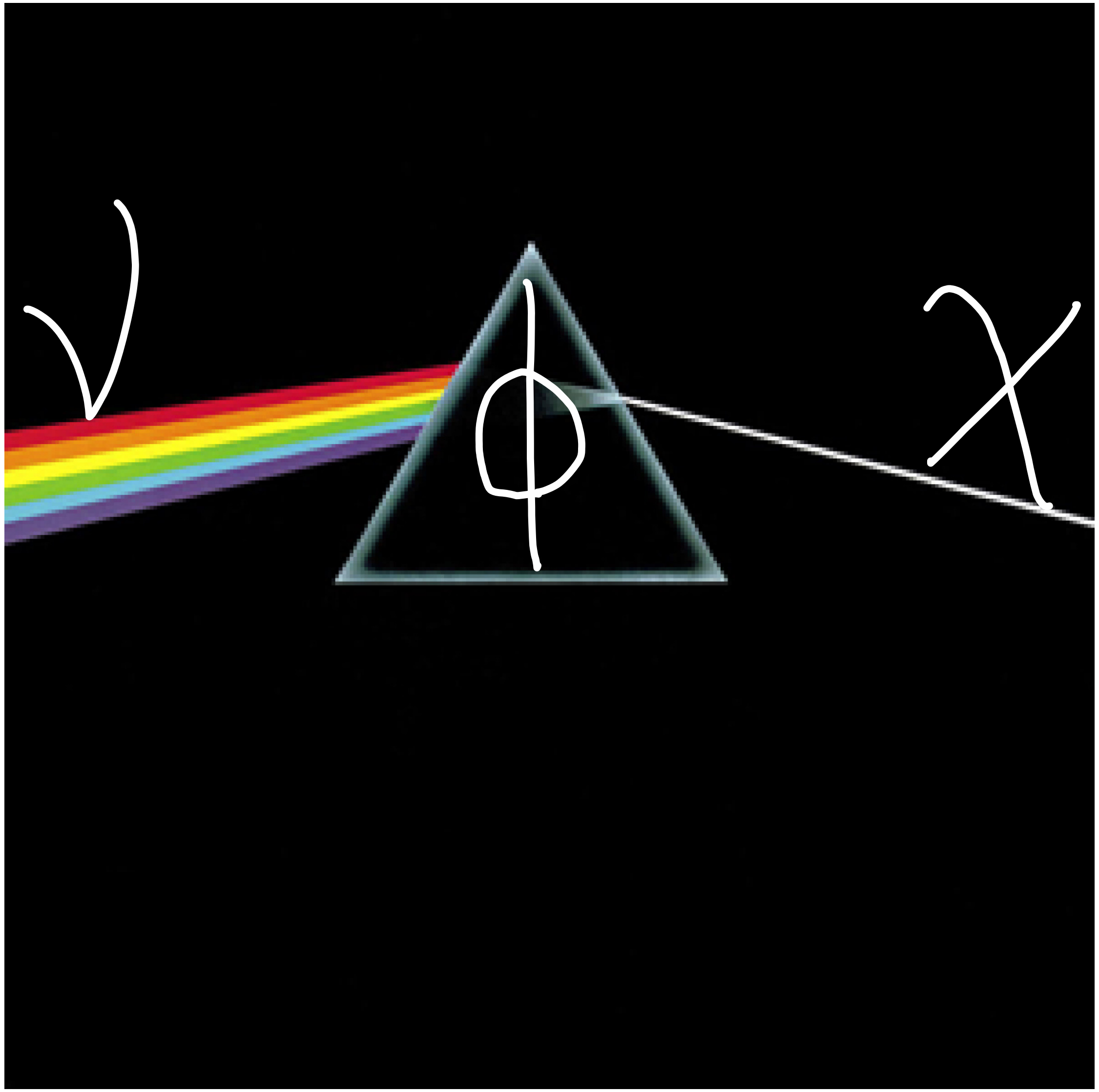
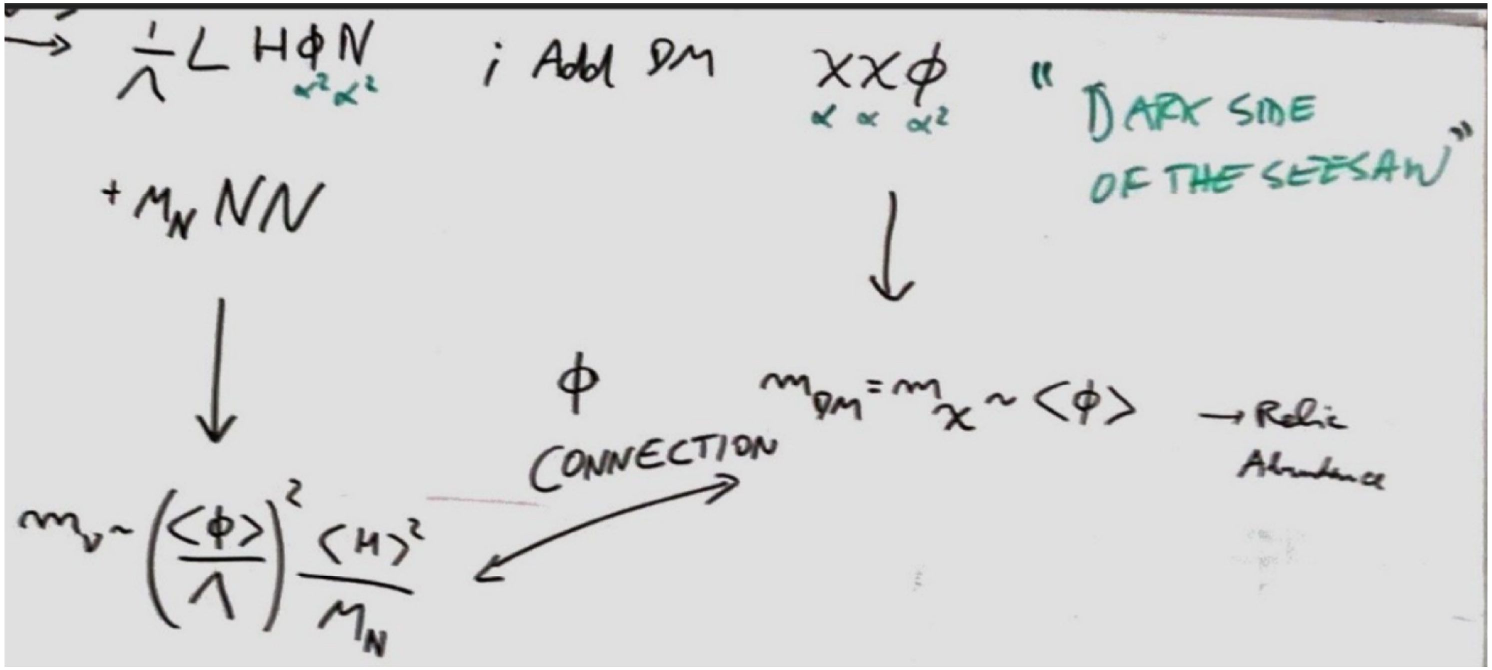
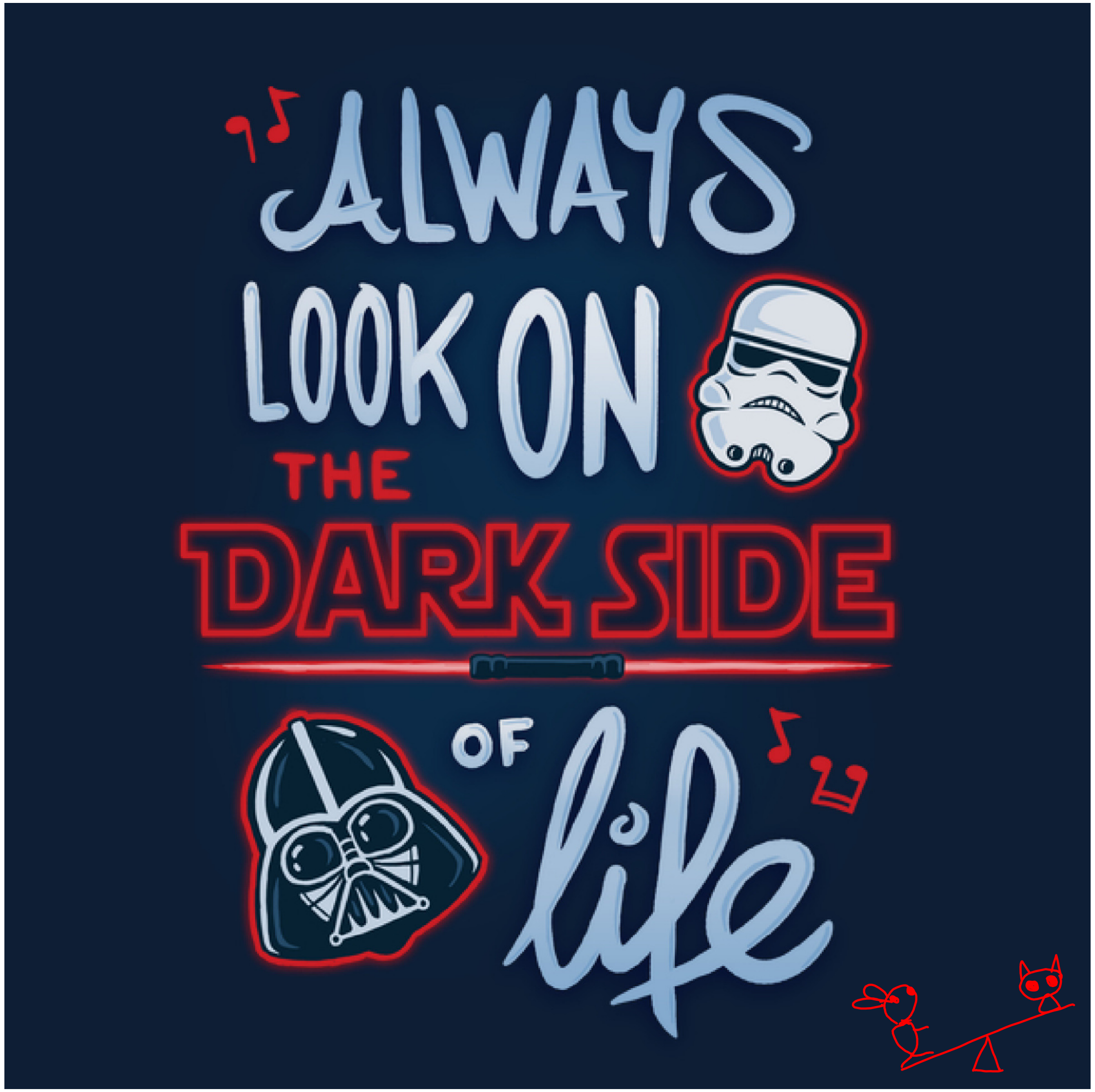
2016/09/09

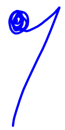

ν
ϕ
χ

Idea from 2016





Life is a
piece of
Sith,



When you
Luke
at it...

Paper from 2018

Dark side of the Seesaw

Subhaditya Bhattacharya, Ivo de Medeiros Varzielas, Biswajit Karmakar, Stephen F. King, Arunansu Sil

(Submitted on 1 Jun 2018)

In an attempt to unfold (if any) a possible connection between two apparently uncorrelated sectors, namely neutrino and dark matter, we consider the type-I seesaw and a fermion singlet dark matter to start with. Our construction suggests that there exists a scalar field mediator between these two sectors whose vacuum expectation value not only generates the mass of the dark matter, but also takes part in the neutrino mass generation. While the choice of Z_4 symmetry allows us to establish the framework, the vacuum expectation value of the mediator field breaks Z_4 to a remnant Z_2, that is responsible to keep dark matter stable. Therefore, the observed light neutrino masses and relic abundance constraint on the dark matter, allows us to predict the heavy seesaw scale as illustrated in this paper.The methodology to connect dark matter and neutrino sector, as introduced here, is a generic one and can be applied to other possible neutrino mass generation mechanism and different dark matter candidate(s).

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(or **arXiv:1806.00490v1 [hep-ph]** for this version)

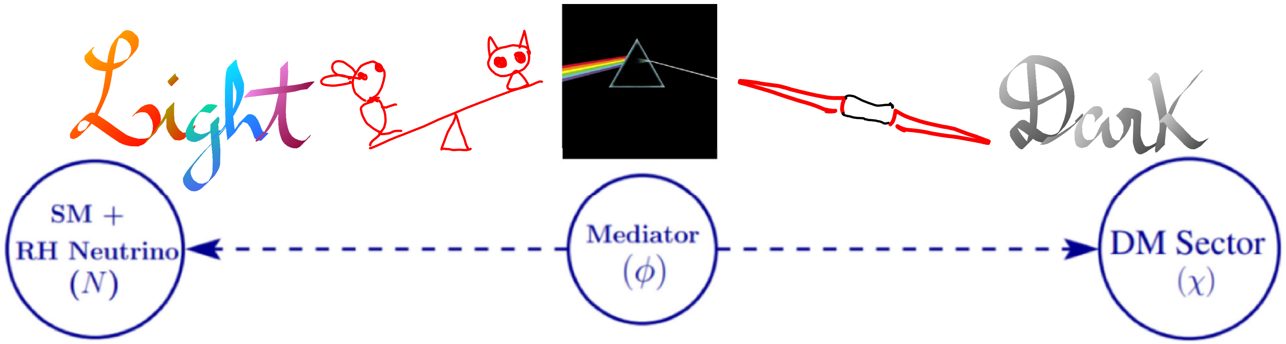


Figure 1: Schematic representation for DM interaction with SM trough the scalar ϕ

Field	L	H	N	ϕ	χ
Z_4	0	0	2	2	1

Table 1: Transformation properties fields involved under Z_4 in additive notation where charge q means: the field transforms like $e^{i2\pi q/4}$.

Z_4

Field	L	H	N	ϕ	χ
Z_4	0	0	2	2	1

Table 1: Transformation properties fields involved under Z_4 in additive notation where charge q means: the field transforms like $e^{i2\pi q/4}$.

Z_4

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\bar{L}\tilde{H}\phi N + M_N \bar{N}^c N + y\phi\bar{\chi}^c\chi + V(H,\phi)$$

2 2 2 2 2 1 1

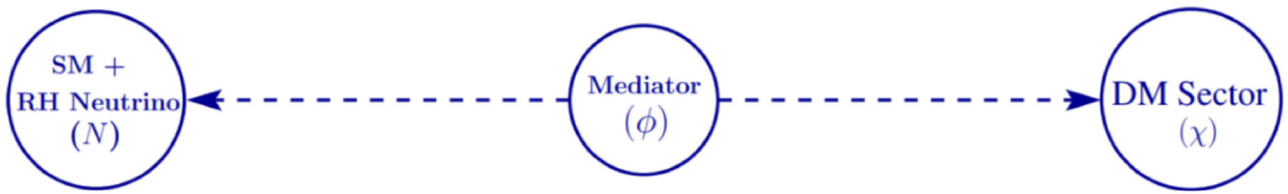
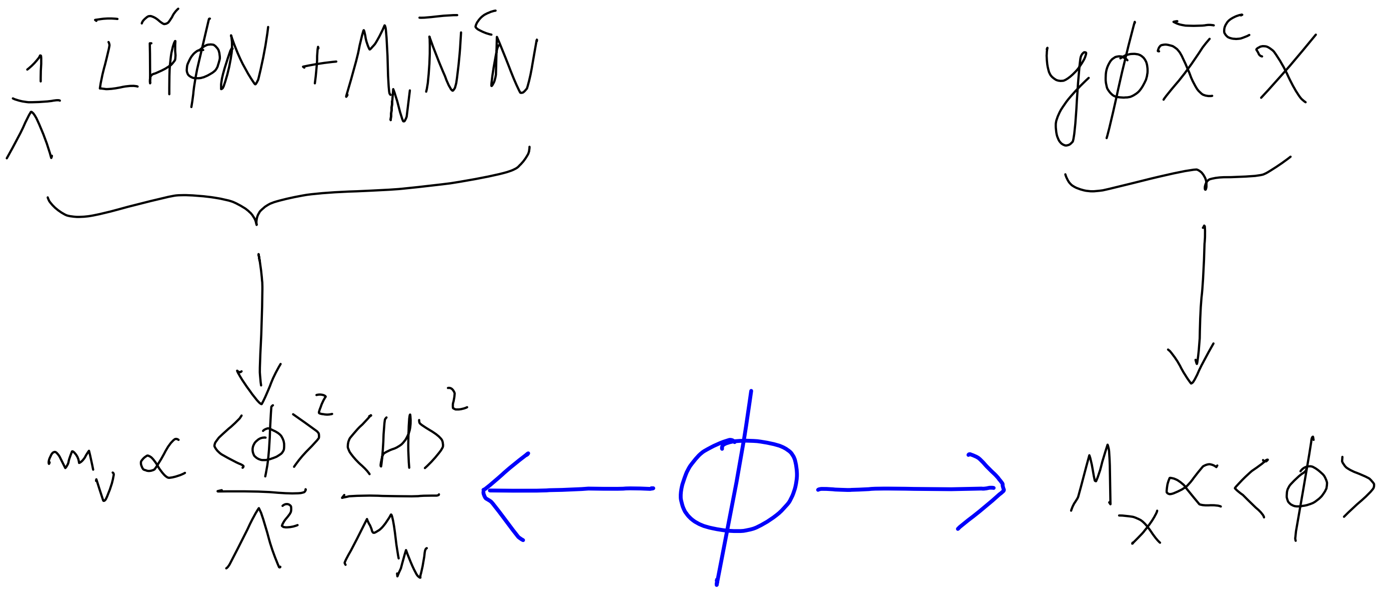


Figure 1: Schematic representation for DM interaction with SM trough the scalar ϕ



$$V(H,\phi) = -\mu_1^2 H^\dagger H + \lambda_1 (H^\dagger H)^2 - \frac{1}{2}\mu_2^2\phi^2 + \frac{1}{4}\lambda_2\phi^4 + \underbrace{\frac{1}{2}\lambda_{12}\phi^2 H^\dagger H}_{\text{Portal}}$$

$H = \begin{pmatrix} 0 \\ v+\tilde{h} \end{pmatrix}/\sqrt{2}$ → $\quad\quad$ ← $\phi = u + h'$

$$M^2_{\tilde{h},h'} = \begin{pmatrix} 2\lambda_1 v^2 & \lambda_{12} v u \\ \lambda_{12} v u & 2\lambda_2 u^2 \end{pmatrix}$$

Diagonalise

↓

Mass eigenstates

h, H'

↓

m_h, $m_{H'}$, $\sin\theta$

Simplifying assumption: $\lambda_1 = \lambda_2 = \lambda$ (general case in App)

$$m_h^2 = \lambda(v^2 + u^2) - \sqrt{\lambda^2(v^2 - u^2)^2 + \lambda_{12}^2 u^2 v^2}$$

$$m_{H'}^2 = \lambda(v^2 + u^2) + \sqrt{\lambda^2(v^2 - u^2)^2 + \lambda_{12}^2 u^2 v^2}$$

$$\sin 2\theta = \frac{\lambda_{12} uv}{\sqrt{(\lambda_1 v^2 - \lambda_2 u^2)^2 + \lambda_{12}^2 u^2 v^2}}$$

Two options :

1. $m_{H'} = m_{h_{SM}}$ & $m_h = m_{H_{light}}$, with $H_{light} \sim h'(\phi)$

$\sin\theta \gtrsim 0.9$

"Low mass region"

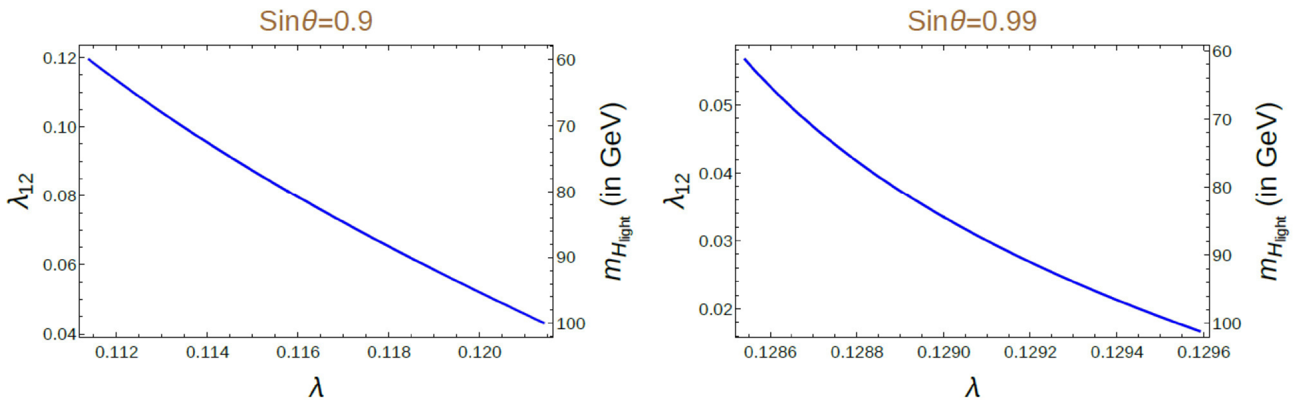
2. $m_h = m_{h_{SM}}$ & $m_{H'} = m_{H_{heavy}}$

$\sin\theta \lesssim 0.3$

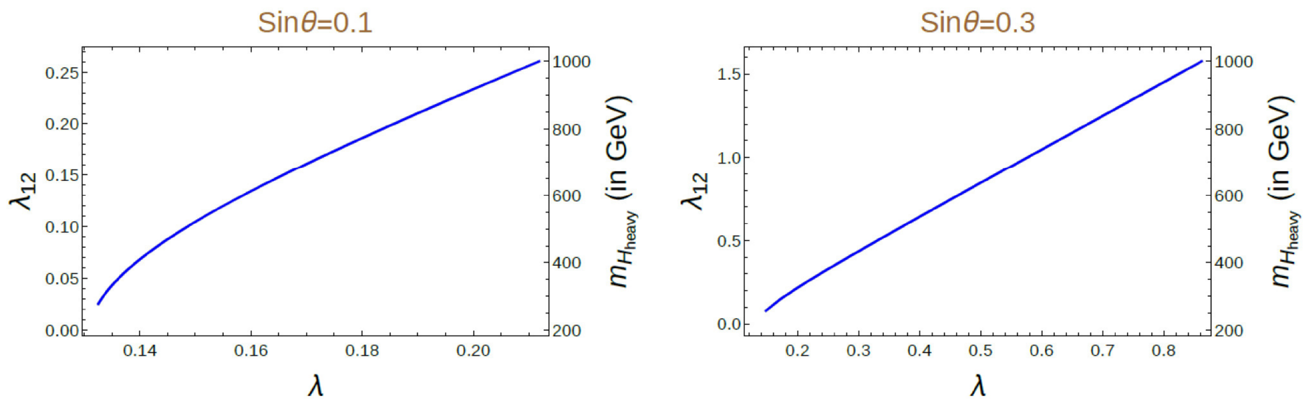
"High mass region"

$m_{h_{SM}}$ fixed ; fixing $m_{H_{light}}$ or $m_{H_{heavy}}$ and $\sin\theta$ . . .

1.



2.



$\langle \phi \rangle = u$ depends on V...

1.

Benchmark Points $m_{H_{\rm light}}$ (GeV)	u (GeV)		λ		λ_{12}	
	$s_\theta = 0.999$	$s_\theta = 0.9$	$s_\theta = 0.999$	$s_\theta = 0.9$	$s_\theta = 0.999$	$s_\theta = 0.9$
60	117.91	162.98	0.1303	0.1114	0.0188	0.1194
80	156.89	188.01	0.1304	0.1158	0.0109	0.0797
100	195.89	213.80	0.0827	0.1214	0.0034	0.0433

Table 2: Vacuum Expectation value of singlet scalar (u) and the dimensionless couplings in the scalar potential ($\lambda_1 = \lambda_2 = \lambda, \lambda_{12}$) evaluated at some selected benchmark points for $m_{H_{\rm light}}$ =60, 80, and 100 GeV with $\sin\theta = 0.999(0.90)$, $m_{h_{\rm SM}} = 125.7$ GeV with SM Higgs vev $v = 246$ GeV.

2.

Benchmark Points $m_{H_{\rm heavy}}$ (GeV)	u (GeV)		λ		λ_{12}	
	$s_\theta = 0.3$	$s_\theta = 0.001$	$s_\theta = 0.3$	$s_\theta = 0.001$	$s_\theta = 0.3$	$s_\theta = 0.001$
200	356.81	391.41	0.1485	0.1306	0.0789	0.0003
400	556.02	782.81	0.2378	0.1306	0.3017	0.0008
600	662.42	1174.21	0.3865	0.1306	0.6138	0.0012
800	700.61	1565.60	0.5947	0.1306	1.0365	0.0016
1000	726.93	1956.98	0.8624	0.1306	1.5751	0.0020

Table 3: Values obtained for $\lambda_1 = \lambda_2 = \lambda$ and vev u (in GeV) for some chosen heavy Higgs masses $m_{H_{\rm heavy}}$ = 200, 400, 600 and 1000 GeV and two extreme values of mixing angles $\sin\theta = 0.3$ (0.001), $m_{h_{\rm SM}} = 125.7$ GeV and $v = 246$ GeV.

DM Pheno

3 Parameters: M_χ, $\sin\theta$, $m_{H_{light}}$ or $m_{H_{heavy}}$

$(\lambda_1 = \lambda_2 = \lambda)$

Z_4:

No ϕ^3

$M_\chi \uparrow \langle \phi \rangle \downarrow m_\nu$

DM Relic Density

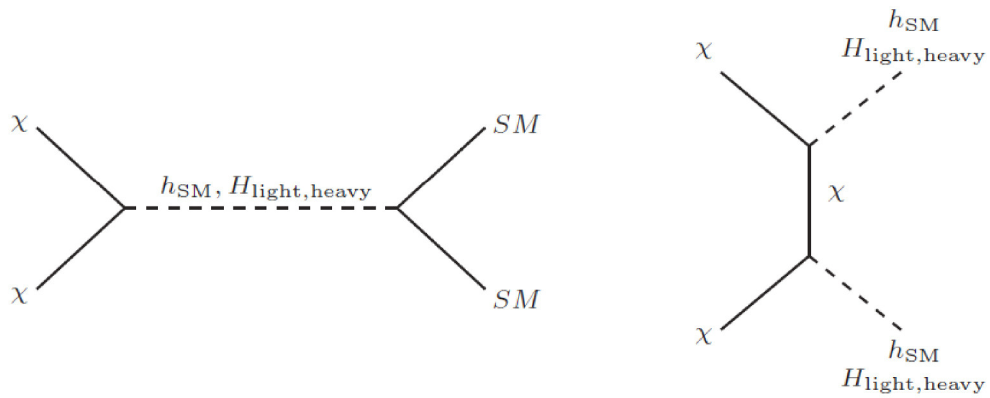
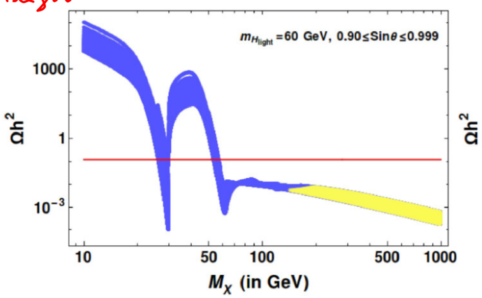


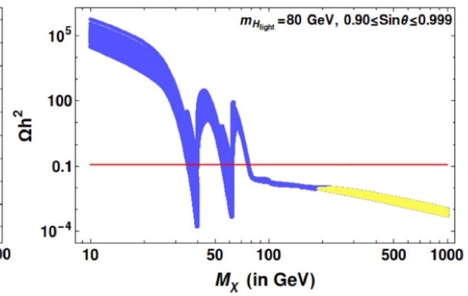
Figure 4: DM (χ) annihilation process that yield relic density of the DM.

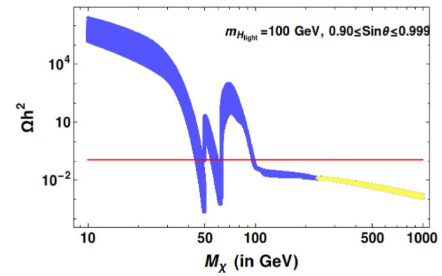
Relic Density

$m_{H_{light}}$ = 60 80 100

1.

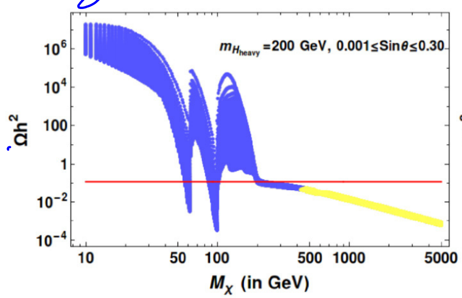


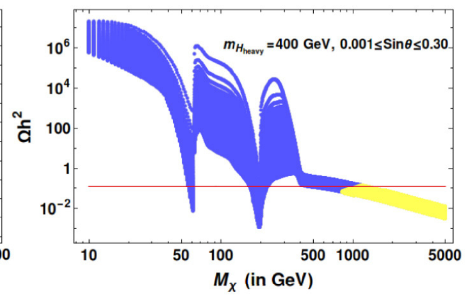


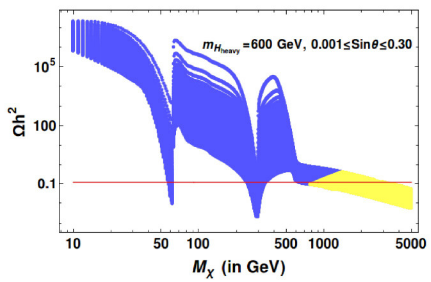


$m_{H_{heavy}}$ = 200 400 600

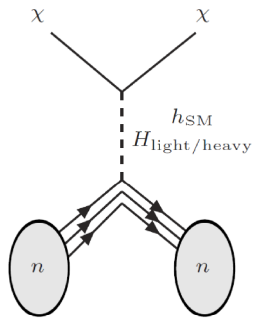
2.







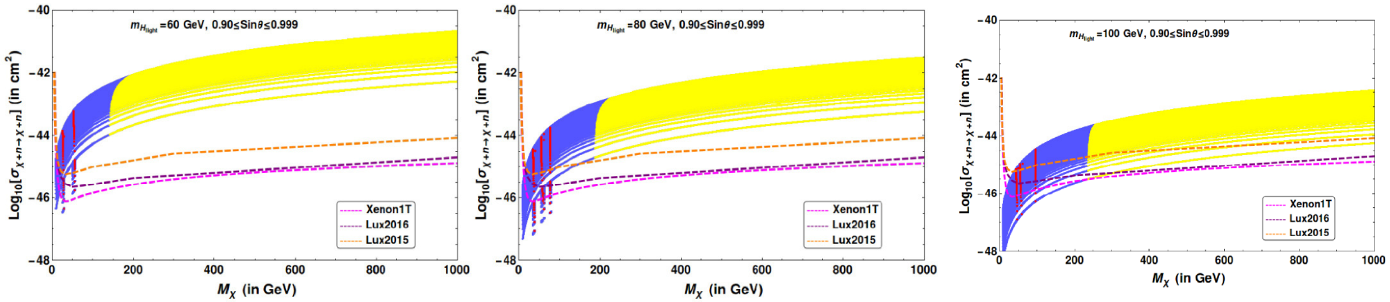
Direct search



Red dots satisfy relic density

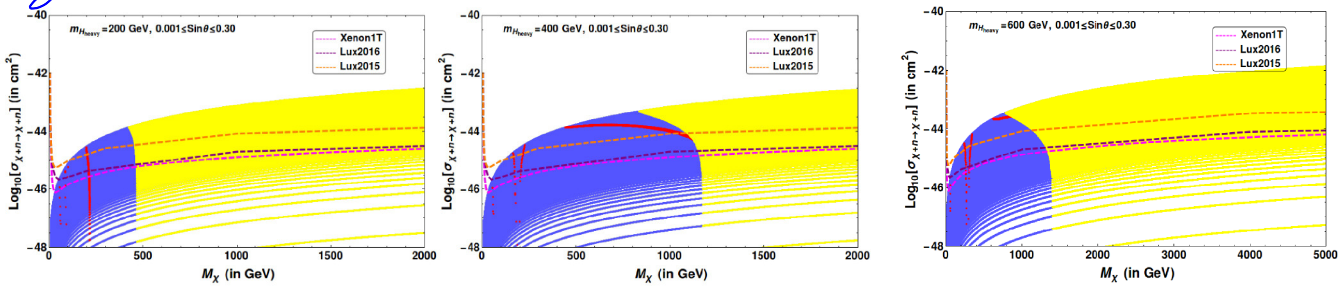
$m_{H_{light}}$ = 60 80 100

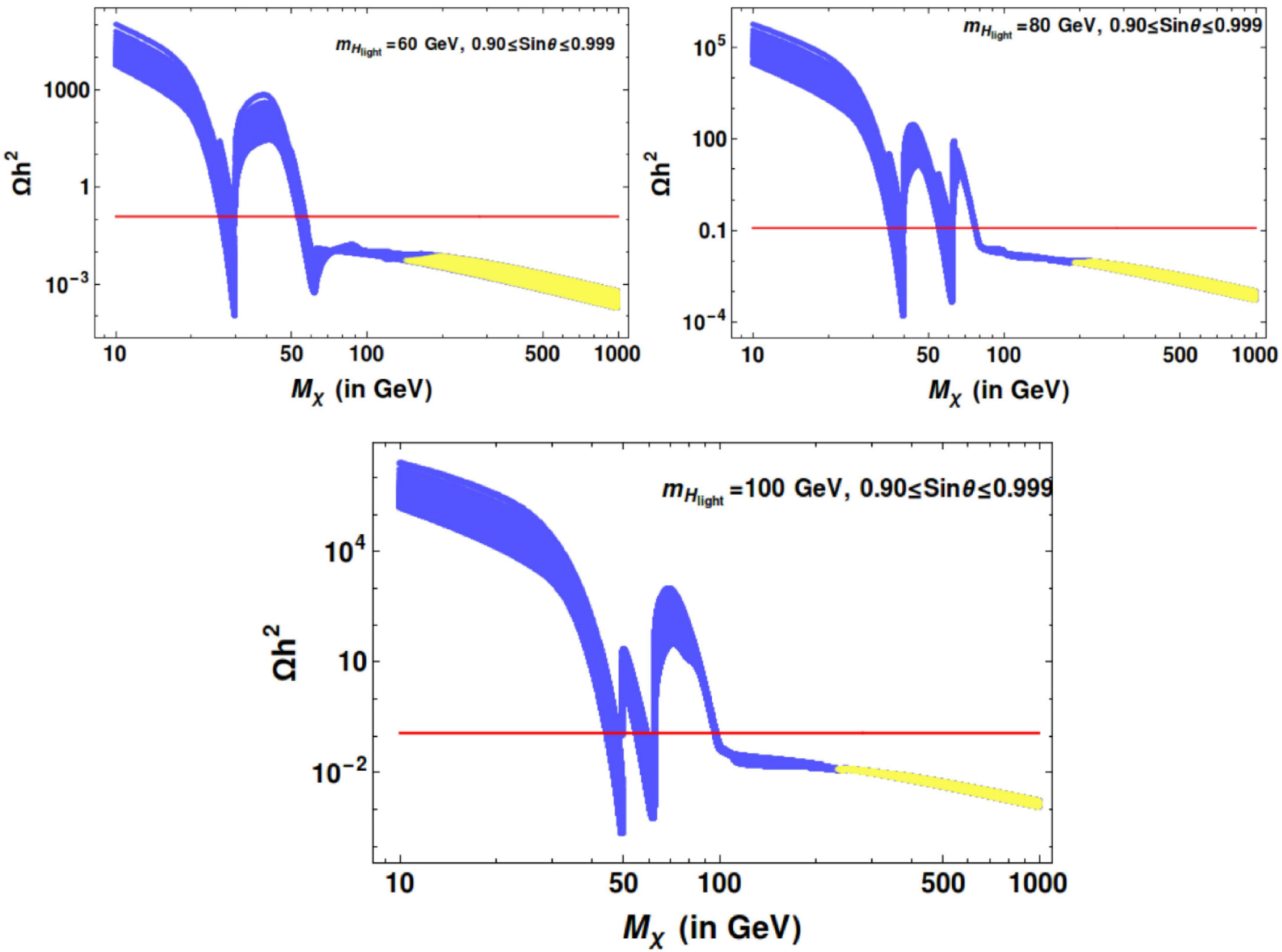
1.



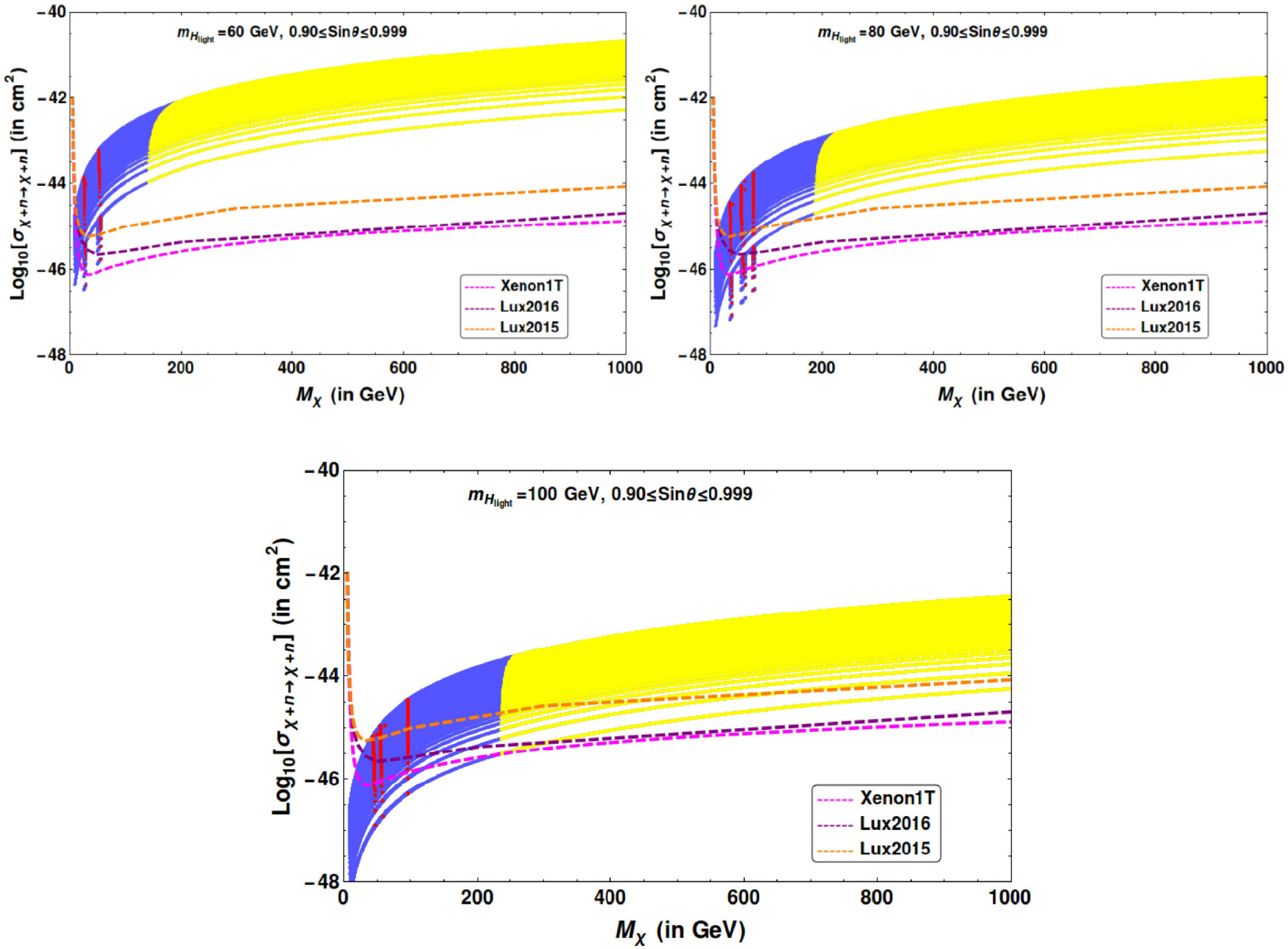
$m_{H_{heavy}}$ = 200 400 600

2.

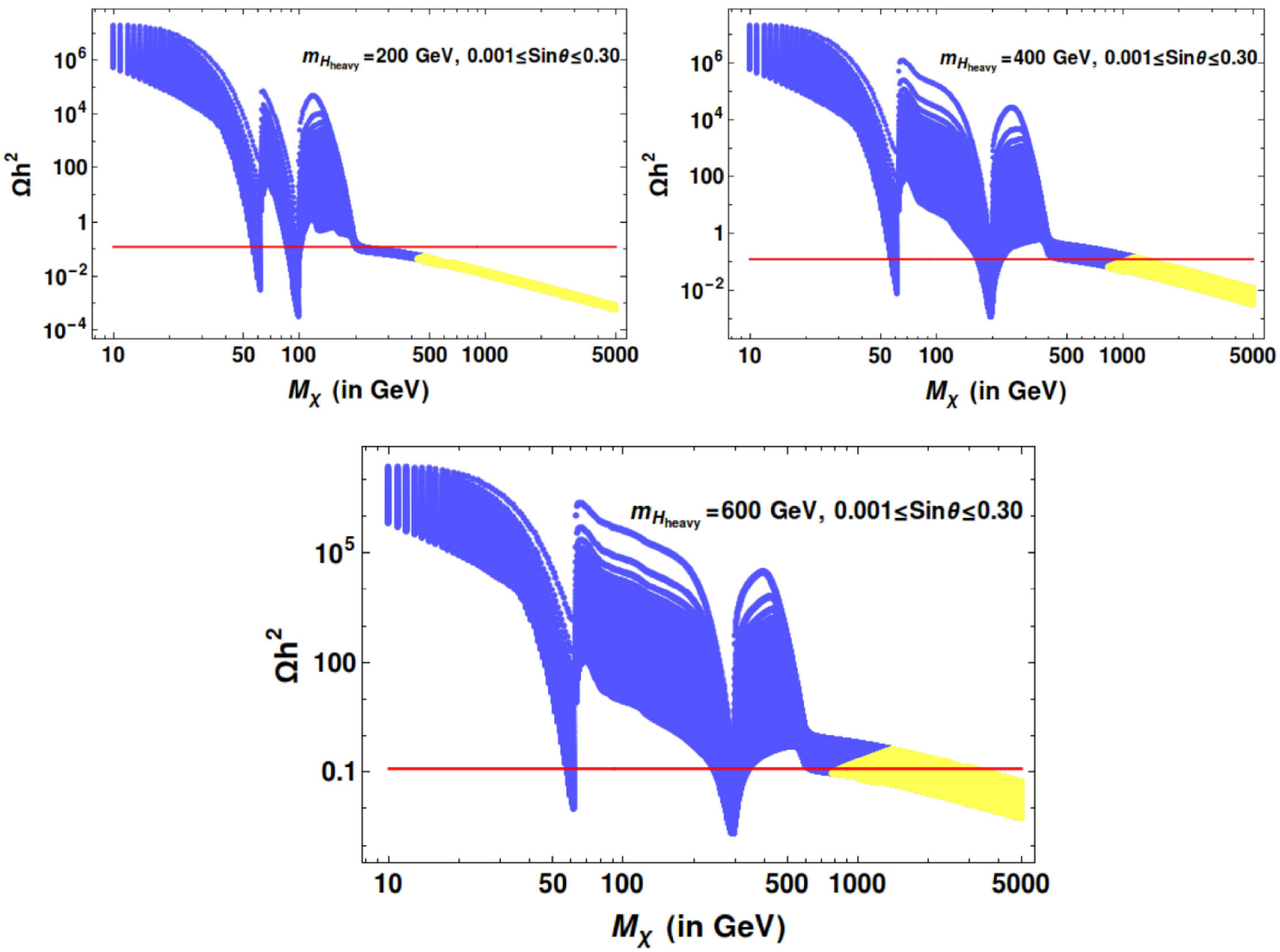




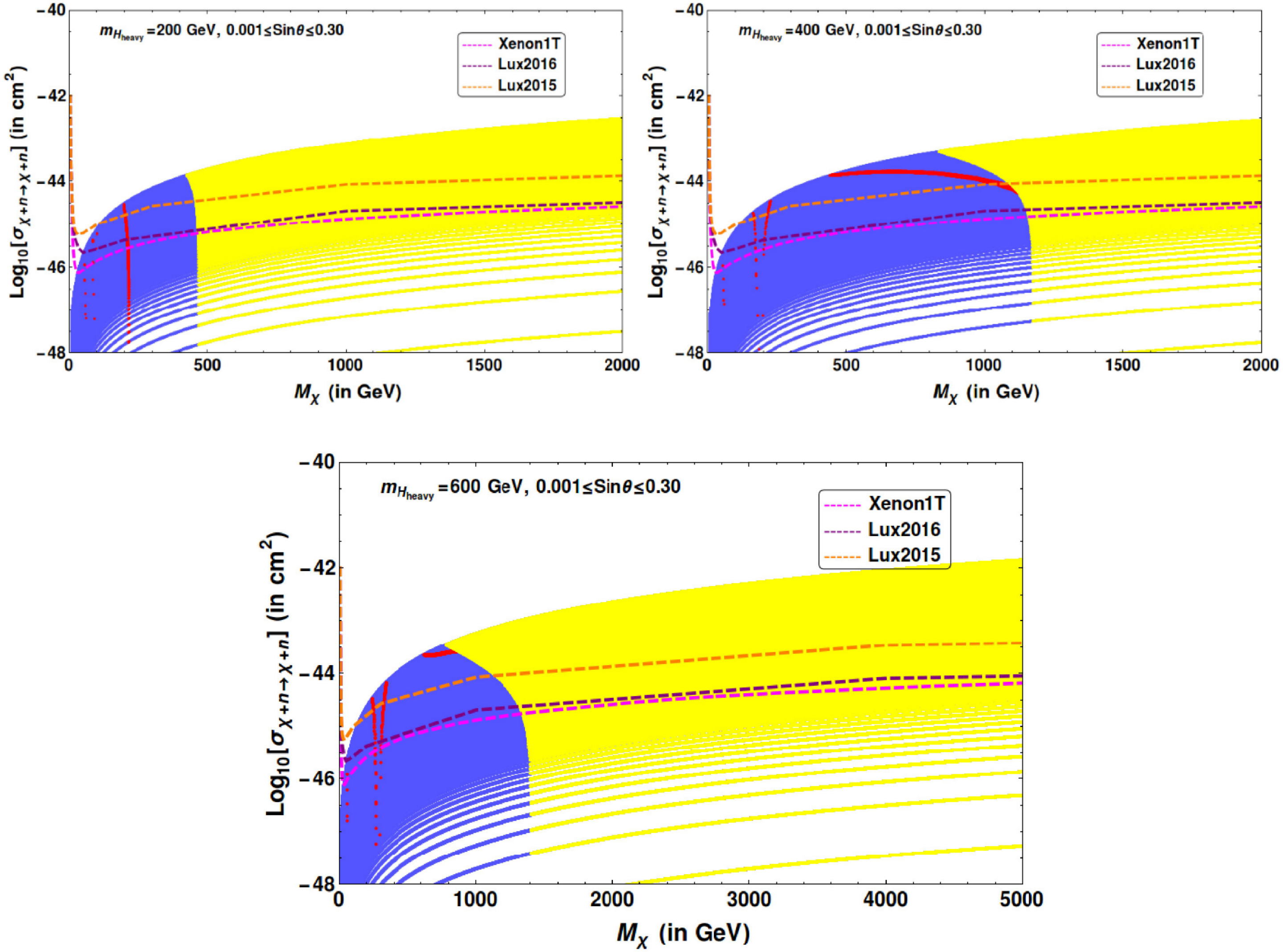
$m_{H_{light}}$ =60 GeV, 0.90≤Sinθ≤0.999
1000
1
10^{-3}
Ωh^2
10
50
100
500
1000
M_χ (in GeV)
$m_{H_{light}}$ =80 GeV, 0.90≤Sinθ≤0.999
10^5
100
0.1
10^{-4}
Ωh^2
10
50
100
500
1000
M_χ (in GeV)
$m_{H_{light}}$ =100 GeV, 0.90≤Sinθ≤0.999
10^4
10
10^{-2}
Ωh^2
10
50
100
500
1000
M_χ (in GeV)



$m_{H_{light}}$ =60 GeV, 0.90≤Sinθ≤0.999
$\mathrm{Log}_{10}[\sigma_{\chi+n\to\chi+n}]$ (in cm^2)
M_χ (in GeV)
Xenon1T
Lux2016
Lux2015
-40
-42
-44
-46
-48
0
200
400
600
800
1000
$m_{H_{light}}$ =80 GeV, 0.90≤Sinθ≤0.999
$\mathrm{Log}_{10}[\sigma_{\chi+n\to\chi+n}]$ (in cm^2)
M_χ (in GeV)
Xenon1T
Lux2016
Lux2015
$m_{H_{light}}$ =100 GeV, 0.90≤Sinθ≤0.999
$\mathrm{Log}_{10}[\sigma_{\chi+n\to\chi+n}]$ (in cm^2)
M_χ (in GeV)
Xenon1T
Lux2016
Lux2015



$m_{H_{heavy}}$=200 GeV, 0.001≤Sinθ≤0.30
$m_{H_{heavy}}$=400 GeV, 0.001≤Sinθ≤0.30
$m_{H_{heavy}}$=600 GeV, 0.001≤Sinθ≤0.30
Ωh^2
M_χ (in GeV)
10
50
100
500
1000
5000
10^6
10^4
10^5
100
1
0.1
10^{-2}
10^{-4}



mHheavy=200 GeV, 0.001≤Sinθ≤0.30
Xenon1T
Lux2016
Lux2015
Log10[σχ+n→χ+n] (in cm2)
MX (in GeV)
mHheavy=400 GeV, 0.001≤Sinθ≤0.30
Xenon1T
Lux2016
Lux2015
Log10[σχ+n→χ+n] (in cm2)
MX (in GeV)
mHheavy=600 GeV, 0.001≤Sinθ≤0.30
Xenon1T
Lux2016
Lux2015
Log10[σχ+n→χ+n] (in cm2)
MX (in GeV)

Some viable benchmark points

Mass of the Scalar	$\sin\theta$	λ	λ_{12}	u GeV	y	M_χ GeV	Ωh^2	$\mathrm{Log}_{10}[\sigma_{\mathrm{SI}}]\times 10^{-45}$ cm^2
$m_{H_{\mathrm{light}}}$ =100 GeV	0.993	0.13	0.019	196.99	0.236	46.59	0.118	-46.10
	0.996	0.13	0.011	196.45	0.292	57.46	0.121	-46.15
	0.998	0.13	0.008	196.08	0.496	97.34	0.121	-45.99
	0.999	0.13	0.005	195.89	0.497	97.40	0.119	-46.29
$m_{H_{\mathrm{heavy}}}$ =200 GeV	0.069	0.133	0.017	389.43	0.154	60	0.122	-46.90
	0.031	0.131	.008	391.01	0.233	91	0.119	-47.23
	0.011	0.131	0.003	391.35	0.552	216	0.121	-47.37
$m_{H_{\mathrm{heavy}}}$ =400 GeV	0.129	0.150	0.104	723.90	0.083	60	0.120	-46.55
	0.115	0.146	0.091	735.04	0.278	204	0.118	-45.60
	0.011	0.131	0.008	782.34	1.600	1251	0.120	-46.10
$m_{H_{\mathrm{heavy}}}$ =600 GeV	0.165	0.208	0.248	918.13	0.065	60	0.119	-46.50
	0.093	0.155	0.121	1072.67	0.283	304	0.118	-45.70
	0.011	0.131	0.013	1172.61	2.400	2815	0.120	-45.69

Table 6: Benchmark points for both low and high mass regions satisfying dark matter relic density and direct search constraints.

Seesaw Mechanism

$$m_\nu \propto \frac{\langle\phi\rangle^2}{\Lambda^2}\frac{\langle H\rangle^2}{M_N} \longleftarrow \phi \longrightarrow M_\chi \propto \langle\phi\rangle$$

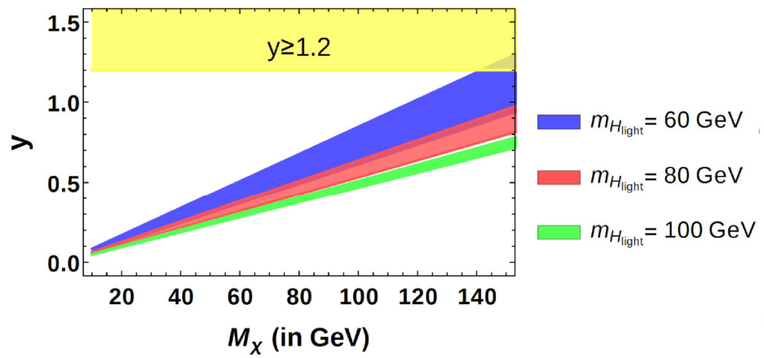
M_χ from Relic density

$$m_\nu = \frac{v^2u^2}{\Lambda^2 M_N} = \frac{v^2}{y^2}\frac{(M_\chi/\Lambda)^2}{M_N} \longleftarrow y \longrightarrow M_\chi = y u$$

because I know u

(u depends on V parameters)

1.



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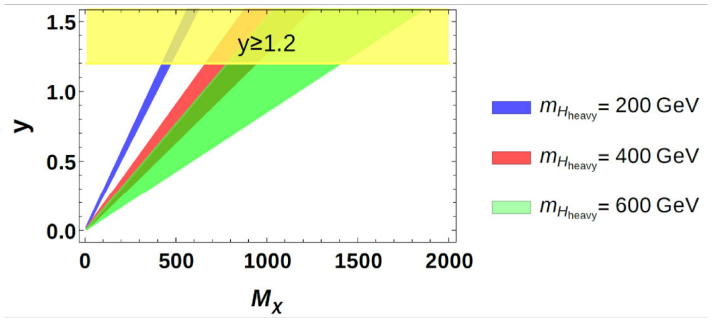
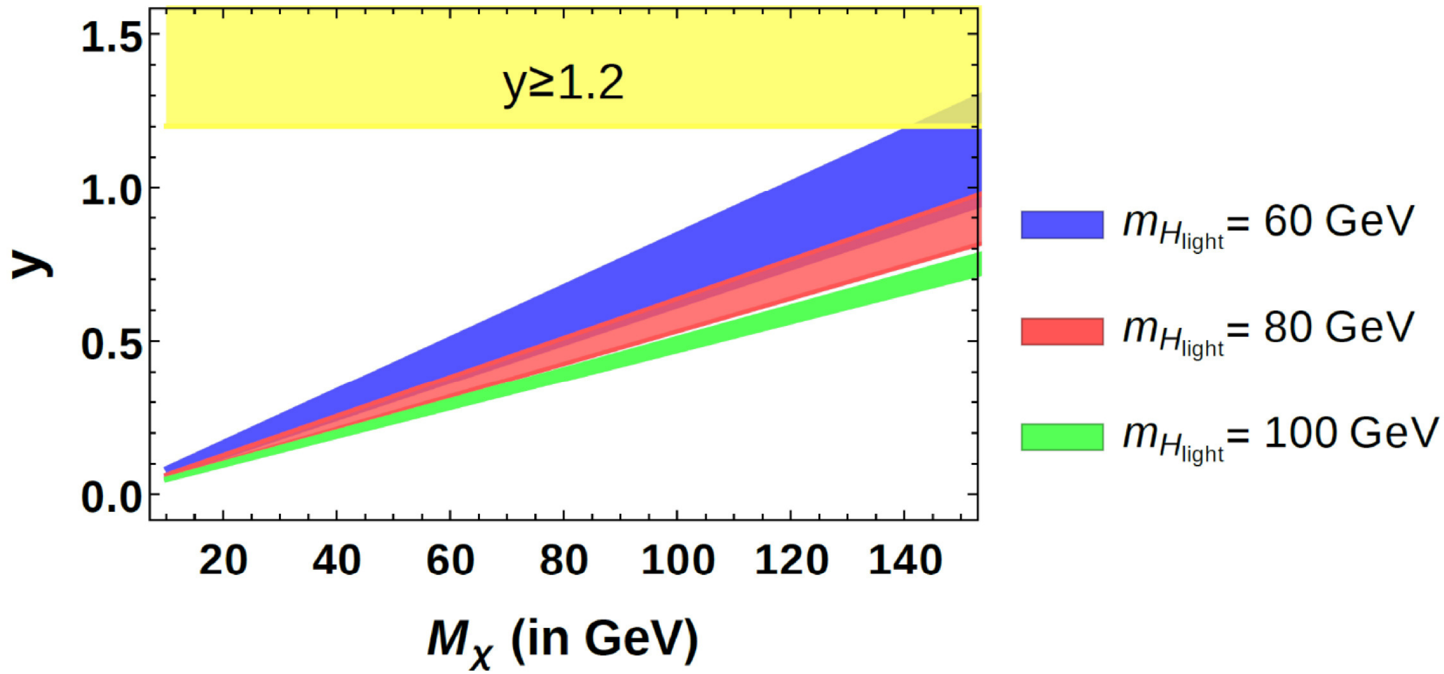
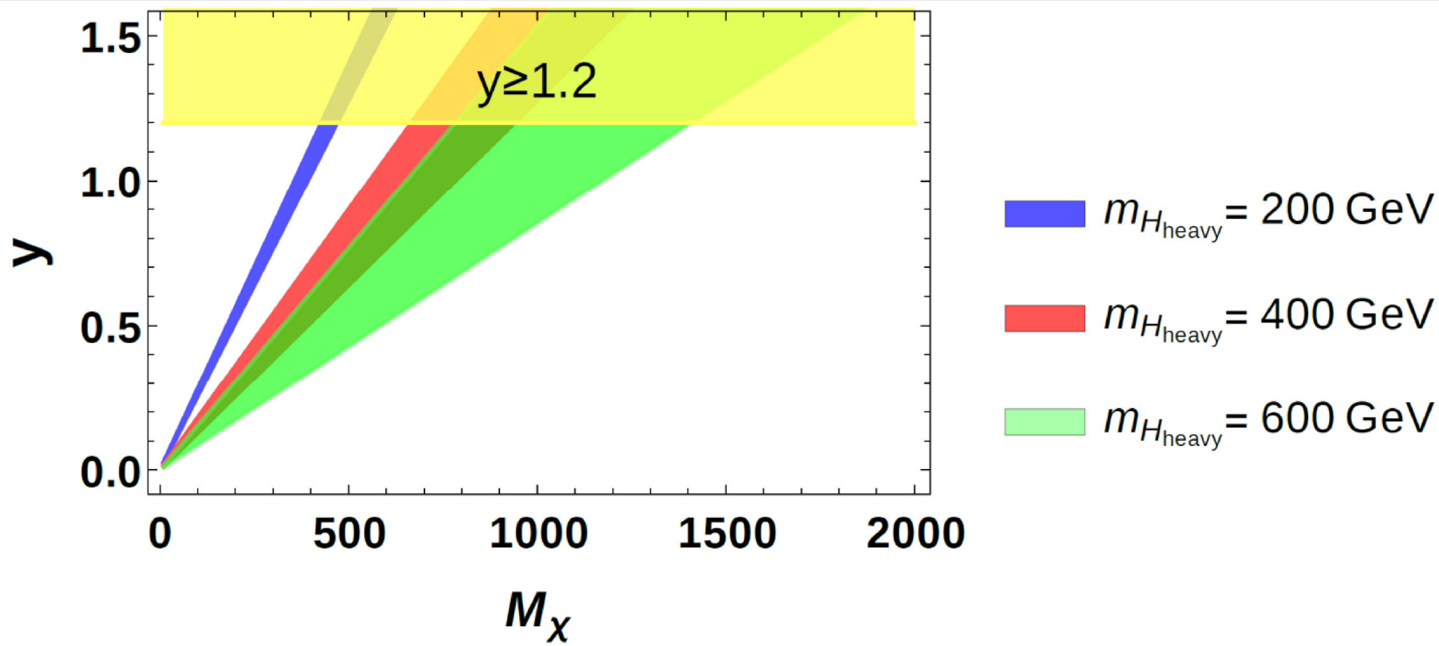


Figure 10: Left: Yukawa coupling (y) vs DM mass M_χ in the low mass region for $m_{H_{\rm light}}$=60, 80 and 100 GeV with $0.90 \leq \sin\theta \leq 0.999$. Right: y vs M_χ for high mass region with $m_{H_{\rm heavy}}$=200, 400, 600, 800 and 1000 GeV for $0.001 \leq \sin\theta \leq 0.3$.



y≥1.2
1.5
1.0
0.5
0.0
y
20
40
60
80
100
120
140
M_χ (in GeV)
$m_{H_{light}}$= 60 GeV
$m_{H_{light}}$= 80 GeV
$m_{H_{light}}$= 100 GeV



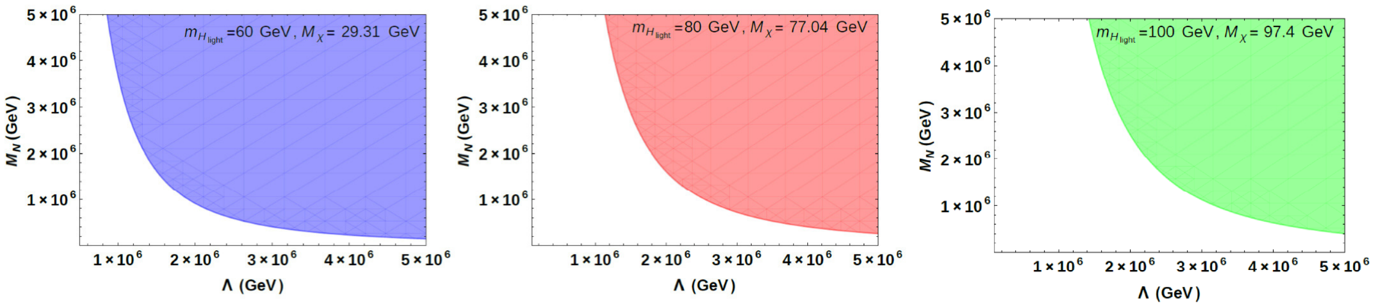
y≥1.2
1.5
1.0
0.5
0.0
y
0
500
1000
1500
2000
M_χ
$m_{H_{heavy}}$ = 200 GeV
$m_{H_{heavy}}$ = 400 GeV
$m_{H_{heavy}}$ = 600 GeV

Cosmological bound: Relate M_N & Λ (for fixed M_χ, know y)

$$m_\nu = \frac{v^2 u^2}{\Lambda^2 M_N} = \frac{v^2}{y^2}\frac{(M_\chi/\Lambda)^2}{M_N} \longrightarrow \frac{v^2}{y^2}\frac{M_\chi^2}{\Lambda^2 M_N} \leq 0.23 \text{ eV}.$$

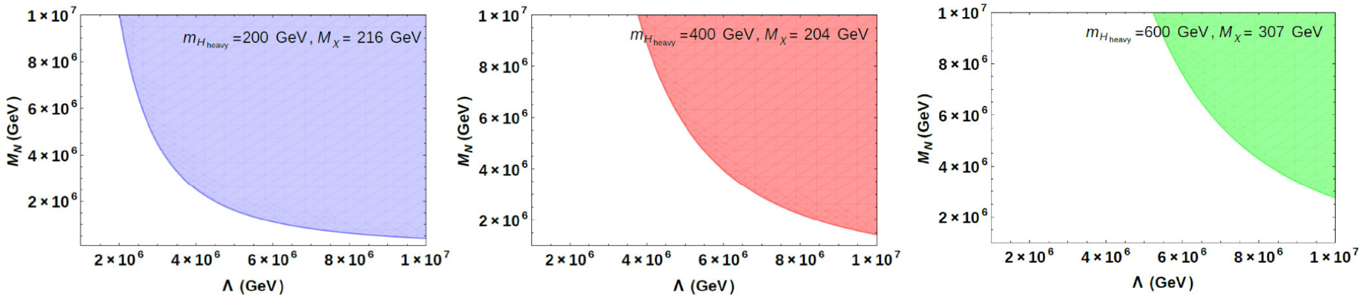
$m_{H\text{light}}$ = 60 80 100

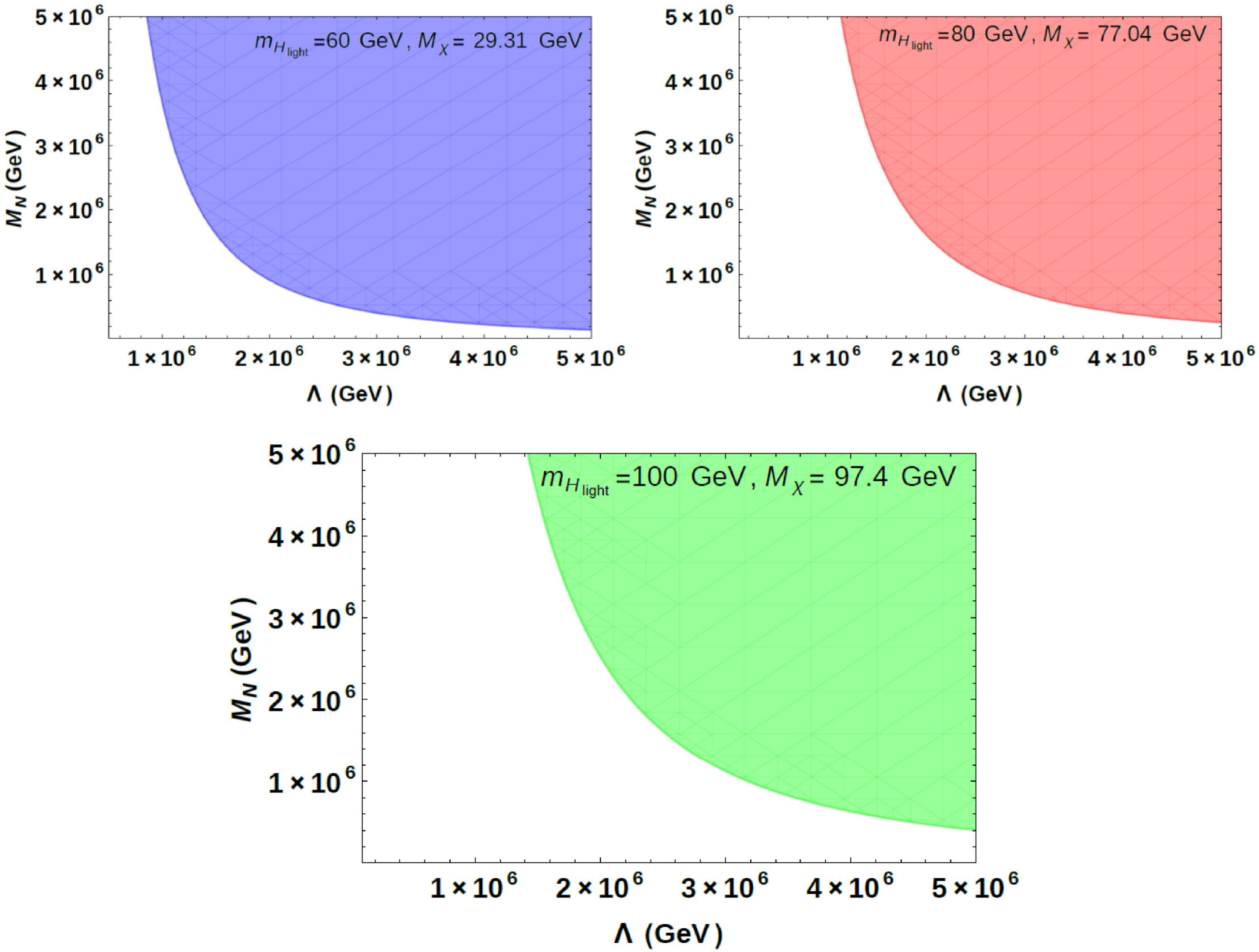
1.



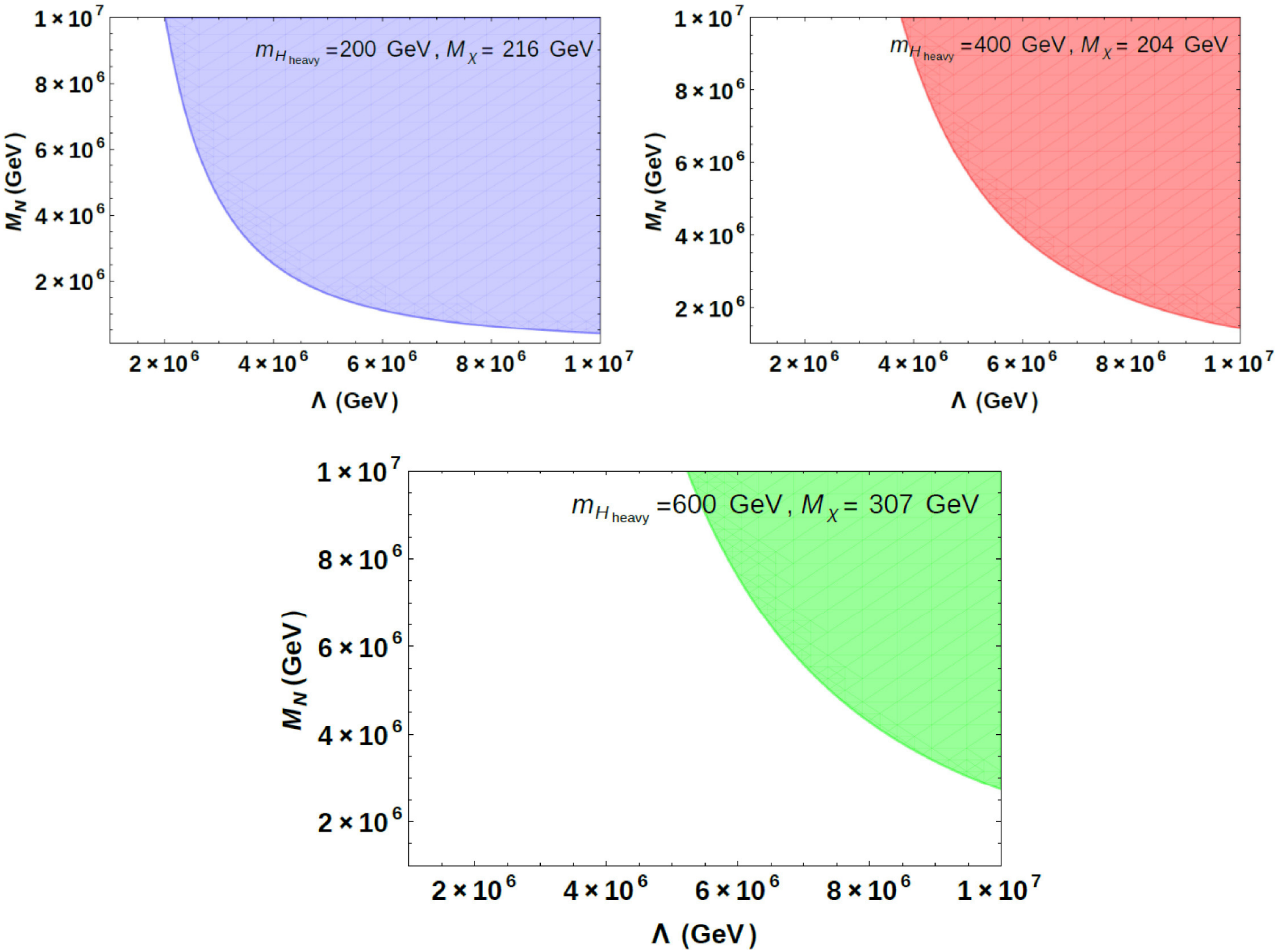
$m_{H\text{heavy}}$ = 200 400 600

2.





$m_{H_{\rm light}}$=60 GeV, M_χ= 29.31 GeV
M_N (GeV)
Λ (GeV)
$m_{H_{\rm light}}$=80 GeV, M_χ= 77.04 GeV
M_N (GeV)
Λ (GeV)
$m_{H_{\rm light}}$=100 GeV, M_χ= 97.4 GeV
M_N (GeV)
Λ (GeV)



$m_{H_{\rm heavy}}$=200 GeV, M_χ= 216 GeV
$m_{H_{\rm heavy}}$=400 GeV, M_χ= 204 GeV
$m_{H_{\rm heavy}}$=600 GeV, M_χ= 307 GeV
M_N (GeV)
Λ (GeV)
1×10^7
8×10^6
6×10^6
4×10^6
2×10^6

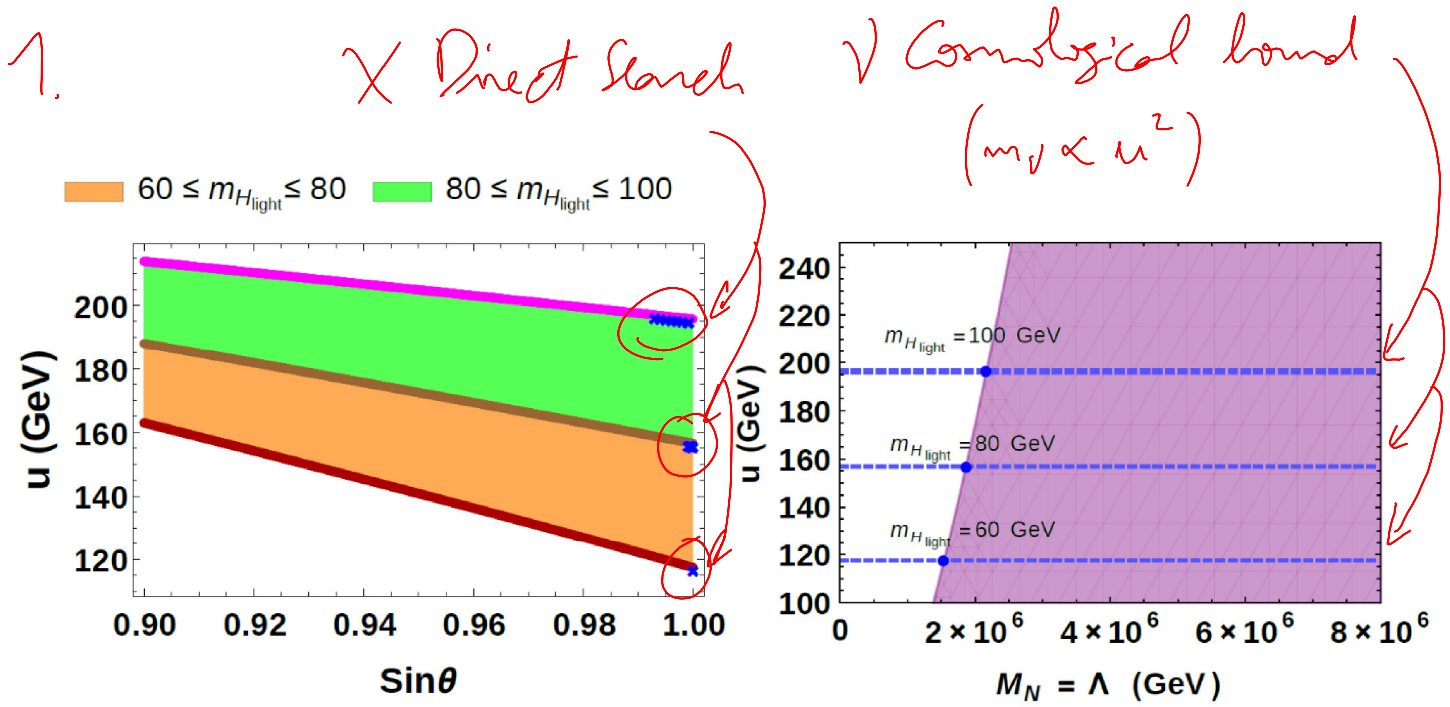


Figure 13: Left panel: $u(= M_\chi/y)$ vs $\sin\theta$ plot for $\lambda_1 = \lambda_2 = \lambda$ for various range of $m_{H_{\rm light}}$. Here the magenta, brown and dark red dots represent allowed points obtained (from Fig. 5) relic density only for $m_{H_{\rm light}} = 100$, 80 and 60 GeV. Blue dots on each line are actual allowed points which also satisfies direct search limit. Right panel: $u(= M_\chi/y)$ as a function of Λ (or M_N) considering $M_N = \Lambda$ in Eq. 21 and 22. Purple shaded region represents $m_\nu \leq 0.23$ eV with $M_N = \Lambda$ and the horizontal blue patch represents the allowed region of $u(= M_\chi/y)$ obtained the left panel. This imposes a stringent constraint on the lower limit of the cut-off scale Λ (and RH neutrino mass M_N).

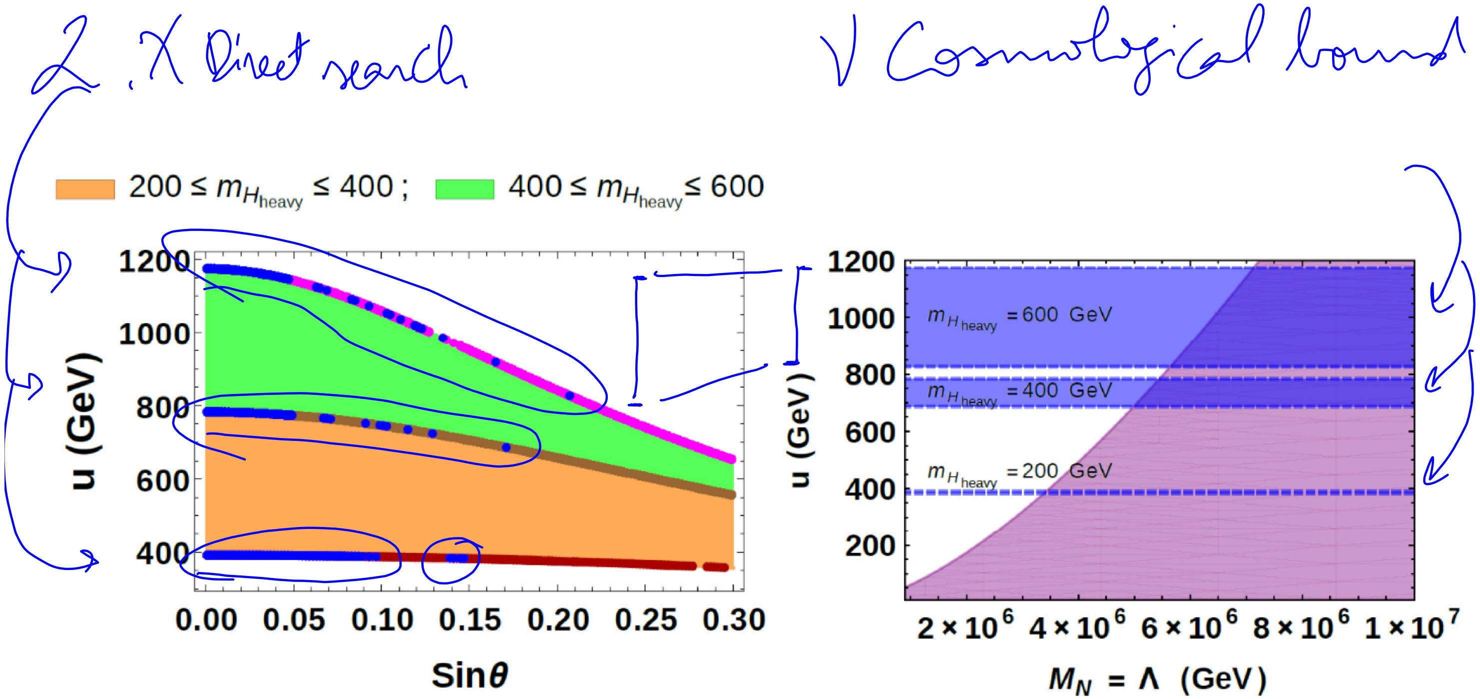
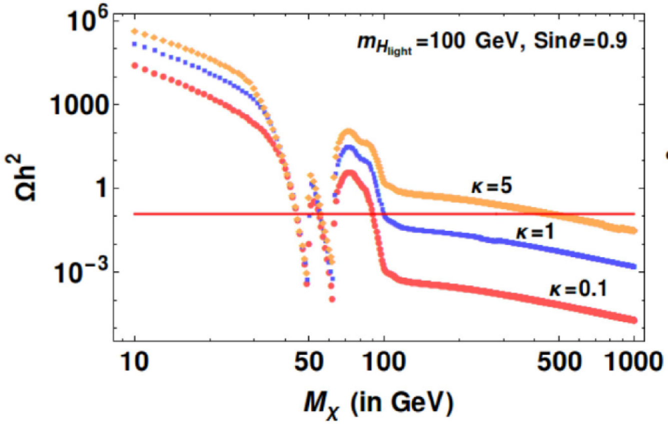
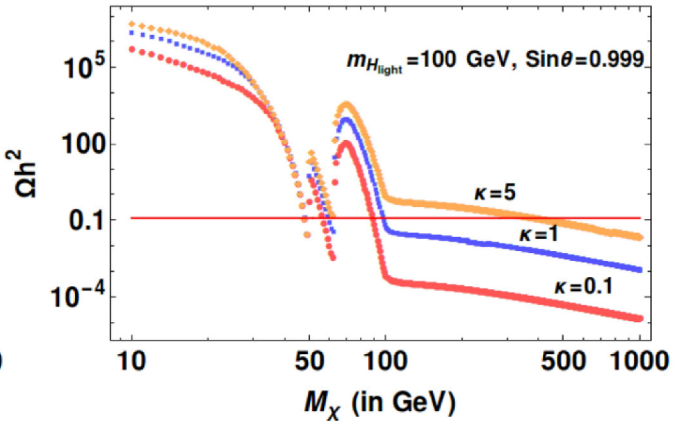


Figure 14: Left panel: $u(= M_\chi/y)$ vs $\sin\theta$ plot for $\lambda_1 = \lambda_2 = \lambda$ for $200 \le m_{H_{\rm heavy}} \le 400$ GeV (orange shaded region) and $400 \le m_{H_{\rm heavy}} \le 600$ GeV (green shaded region) respectively. Here the magenta, brown and deep red dots represent allowed points obtained (from Fig. 8) relic density only, for $m_{H_{\rm light}} = 100$, 80 and 60 GeV. Blue dots on each line are actual allowed points which also satisfies direct search limit. Right panel: $u(= M_\chi/y)$ as a function of Λ (or M_N) considering $M_N = \Lambda$ in Eq. 21 and 22. Purple shaded region represents $m_\nu \le 0.23$ eV with $M_N = \Lambda$ and the horizontal blue patch represents the allowed region of $u(= M_\chi/y)$ obtained the left panel. This imposes a constraint on the lower limit of the cut-off scale Λ (and RH neutrino mass M_N).

$\lambda_1 \neq \lambda_2$; $\kappa \equiv \lambda_1/\lambda_2 \longrightarrow$ Allows bigger range of M_X

1.





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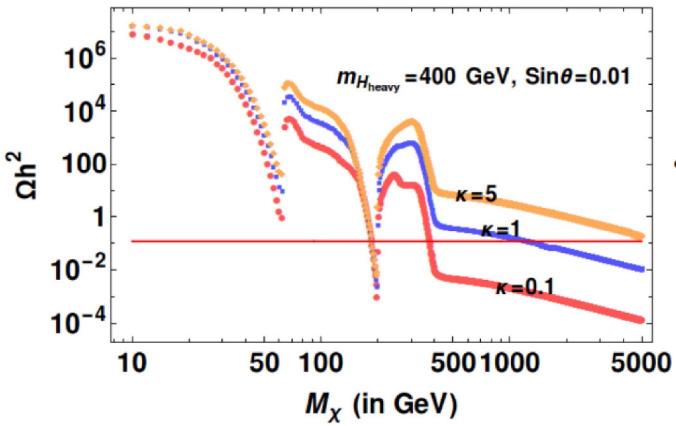

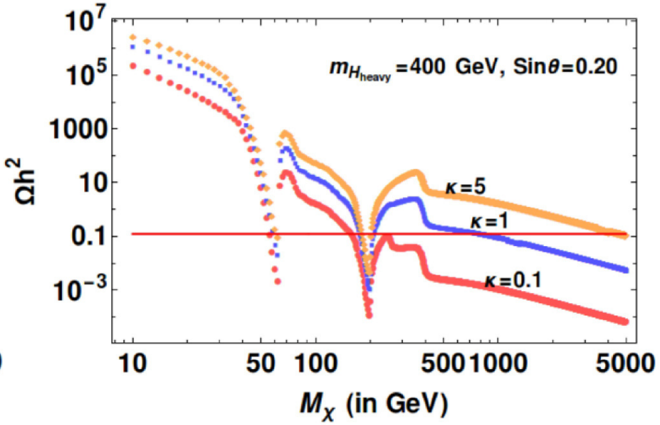

Conclusions

Dark side of the seesaw relates ν & DM through ϕ

DM phenomenology then gives information about

$M_{N}, \Lambda \gtrsim 10^6$ GeV

1. "Low mass region", $M_\chi \sim M_{H_{light}}$, constrained

2. "High mass region", more parameter space

Conclusions

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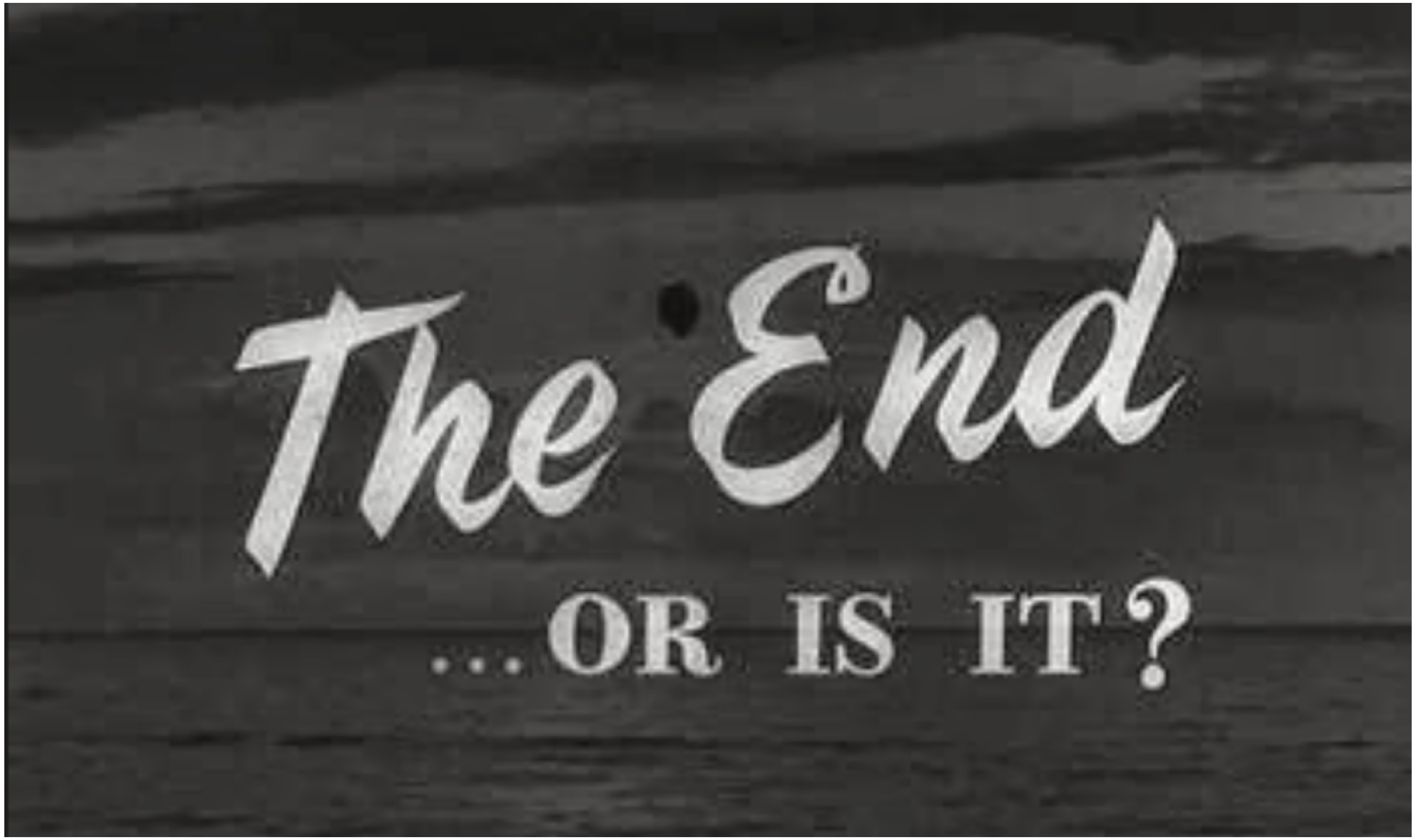
The End?


The End
...OR IS IT?


THE END IS NEAR
THIS WILL NEVER END
YOUR OPTIMISM DISGUSTS ME.
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Non-Abelian family symmetries as portals to dark matter

Ivo de Medeiros Varzielas, Oliver Fischer

(Submitted on 2 Dec 2015)

Non-Abelian family symmetries offer a very promising explanation for the flavour structure in the Standard Model and its extensions. We explore the possibility that dark matter consists in fermions that transform under a family symmetry, such that the visible and dark sector are linked by the familons - Standard Model gauge singlet scalars, responsible for spontaneously breaking the family symmetry. We study three representative models with non-Abelian family symmetries that have been shown capable to explain the masses and mixing of the Standard Model fermions. One of our central results is the possibility to have dark matter fermions and at least one familon with masses on and even below the experimentally accessible TeV scale. In particular we discuss the characteristic signatures in collider experiments from light familon Fields with a non-Abelian family symmetry, and we show that run I of the LHC is already testing this class of models.

Comments: 16 pages plus references
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO)
DOI: 10.1007/JHEP01(2016)160
Cite as: **arXiv:1512.00869 [hep-ph]**
(or **arXiv:1512.00869v1 [hep-ph]** for this version)

Somewhat similar ideas, but with NADS (A_4)

2 Models: ϕ_ℓ & ϕ_ν

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_\chi + \mathscr{L}_\phi \, ;$$

$$\mathscr{L}_\phi = - \, c_{\phi,s} [\phi_\ell \phi_\ell^\dagger]_s [\phi_\ell \phi_\ell^\dagger]_s - c_1 [\phi_\ell \phi_\ell^\dagger]_1 [\phi_\ell \phi_\ell^\dagger]_1 - c_2 [\phi_\ell \phi_\ell^\dagger]_{1'} [\phi_\ell \phi_\ell^\dagger]_{1''} - c_{\phi_\ell H} \underbrace{[\phi_\ell \phi_\ell^\dagger] H^\dagger H}_{\text{Portal}}$$

ϕ_ℓ

	χ	χ_1^c	χ_2^c	χ_3^c	ν^c	L	e^c	μ^c	τ^c	H	ϕ_ℓ
A_4	3	1	$1''$	$1'$	3	3	1	$1''$	$1'$	1	1
$U(1)_{B-L}$	0	0	0	0	1	-1	1	1	1	0	0

Table I: Field assignment within $A_4 \times U(1)_{B-L}$. New fields are gauge singlets with respect to the SM gauge group. The SM gauge charges for the SM fields are unchanged.

A_4 : $\quad \langle \phi_l \rangle = (u, 0, 0)$

$$O_{eff}^{d=5} \supset \frac{H}{\Lambda} \left(y_e [\phi_\ell L_i] e^c + y_\mu [\phi_\ell L_i]' \mu^c + y_\tau [\phi_\ell L_i]'' \tau^c \right)$$

$$\mathscr{L}_\chi \supset -y_{\chi_1} [\phi_\ell \chi] \chi_1^c - y_{\chi_2} [\phi_\ell \chi]' \chi_2^c - y_{\chi_3} [\phi_\ell \chi]'' \chi_3^c$$

$m_\ell \propto u$

↑

$\langle \phi_\ell \rangle$

↓

$m_\chi \propto u$

ϕ_ν

	χ	χ^c	ν^c	L	e^c	μ^c	τ^c	H	ϕ_ν
A_4	3	1	3	3	1	1''	1'	1	3
$U(1)_{B-L}$	0	2	1	−1	1	1	1	0	−2

Table II: Field assignment within $A_4 \times U(1)_{B-L}$. New fields are gauge singlets with respect to the SM gauge group. The SM gauge charges for the SM fields are unchanged.

A_4 :

$$\langle \phi_\nu \rangle = (w, w, w)\,.$$

$$\mathscr{L}_\nu \supset -y_\phi\, \phi_\nu\, [\nu^c \nu^c]_s - y_H \tilde{H}\, [L\nu^c]_s$$

$$\mathscr{L}_{\phi_\nu \chi\chi} = y_\chi [\phi_\nu \chi] \chi^c = y_\chi \phi_{\nu_1} \chi_1 \chi^c + y_\chi \phi_{\nu_2} \chi_3 \chi^c + y_\chi \phi_{\nu_3} \chi_2 \chi^c\,.$$

$M_N \propto w$

↑

$\langle \phi_\nu \rangle$

↓

$M_\chi \propto w$

Conclusions

Interesting connections between

Flavour $\longleftarrow \phi \longrightarrow$ Dark Matter

Thanks

Extra stuff

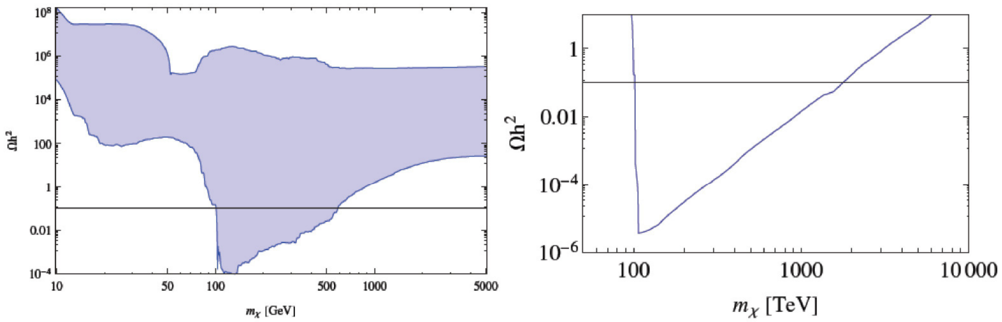
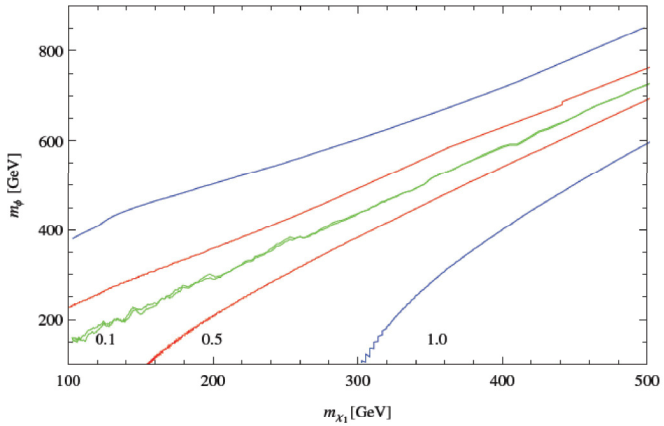


Figure 2: *Left:* Overview of the produced relic density. The model parameters were marginalised within the numerical domains defined in eq. (10). *Right:* Minimal relic densiy, imposing the parameters $y_{\chi i} = c_{\phi H} = 1$ and the relation $m_\chi \simeq 0.5\, m_{\phi^0}$ for resonant s-channel annihilation. Furthermore, $m_\chi := m_{\chi_1}$ and $m_{\chi_{2,3}} = 10$ TeV. The resulting relic density yields the maximum value for m_χ, such that the observation can be matched.

(10)

$$0.01 \le y_{\chi_1} = y_{\chi_2} = y_{\chi_3},\, c_{\phi H} \le 2$$
$$10 \text{ GeV} \le m_{\chi_1}, m_{\chi_2}, m_{\chi_3} \le 10 \text{ TeV}$$
$$100 \text{ GeV} \le m_{\phi_{2,3}} \le 1 \text{ TeV}$$
$$m_{\phi_1} = \sqrt{2} m_{\phi_{2,3}}$$
$$u = \Lambda = 10 \text{ TeV}$$



$M_\chi \propto u$

$\uparrow$

$\langle \phi_\ell \rangle$

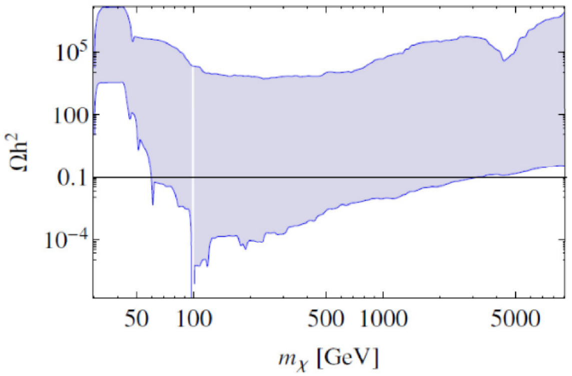
$\downarrow$

$m_\ell \propto u$

Figure 3: Relation between familon and DM masses from the observed relic density, for the familon fields with fixed mass ratios: m_ϕ is the mass of $\phi_{2,3}$ and $m_{\phi_1} = \sqrt{2} m_\phi$. Fixed $u = \Lambda = 1000$ GeV and $m_{\chi_{2,3}} = 10 \times m_{\chi_1}$. The numbers in the plot refer to $y_{\chi_i} = c_{\phi H} = 1.0, 0.5, 0.1$.

(19)

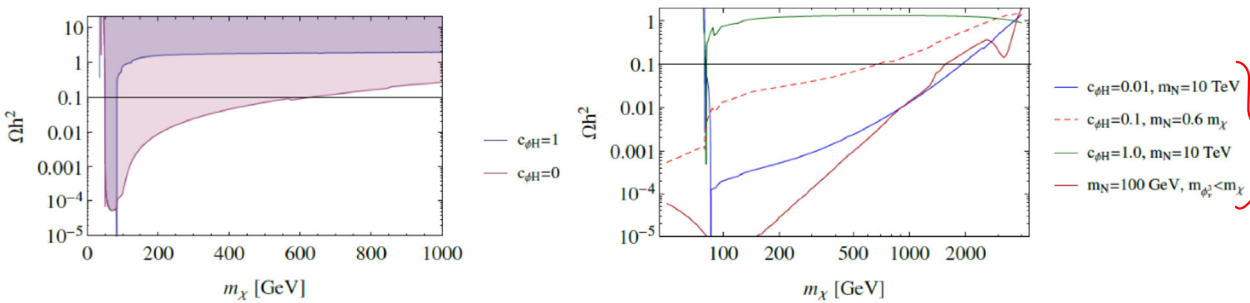
$$10\text{ GeV} \le m_\chi \le 10\text{ TeV}$$
$$100\text{ GeV} \le m_{\phi_\nu^{\text{light}}} \le 1\text{ TeV}$$
$$0.01 \le y_\chi,\, y_{\phi\nu},\, c_{\phi H} \le 2$$
$$m_N = 100\text{ GeV},\; m_{\phi_\nu^{\text{heavy}}} = 10\text{ TeV}$$



$M_\chi \propto w$

Figure 4: Overview of the produced relic density with the non-Abelian familon portal given by ϕ_ν. The model parameters were marginalised within the numerical domains defined in (19).

$\langle \phi_\nu \rangle$



$M_N \propto w$

Figure 5: *Left:* Red line: $c_{\phi H} = 1$, Blue line: $c_{\phi H} = 0.01$. All Yukawa couplings equal one, $m_N = 100$ GeV. *Right:* The blue line is the lower limit on the abundance. It is given by resonant s-channel production of two heavy neutrinos (being lighter than the DM). Relevant parameters controlling the cross section are the respective Yukawa couplings. The two other colored lines are the same, just with $c_{\phi H} = 0.01, 0.1$, respectively. In this case, the scalar parameters are dominating in importance over the neutrino ones.