Vector-like leptonic dark matter, neutrino mass and collider signatures

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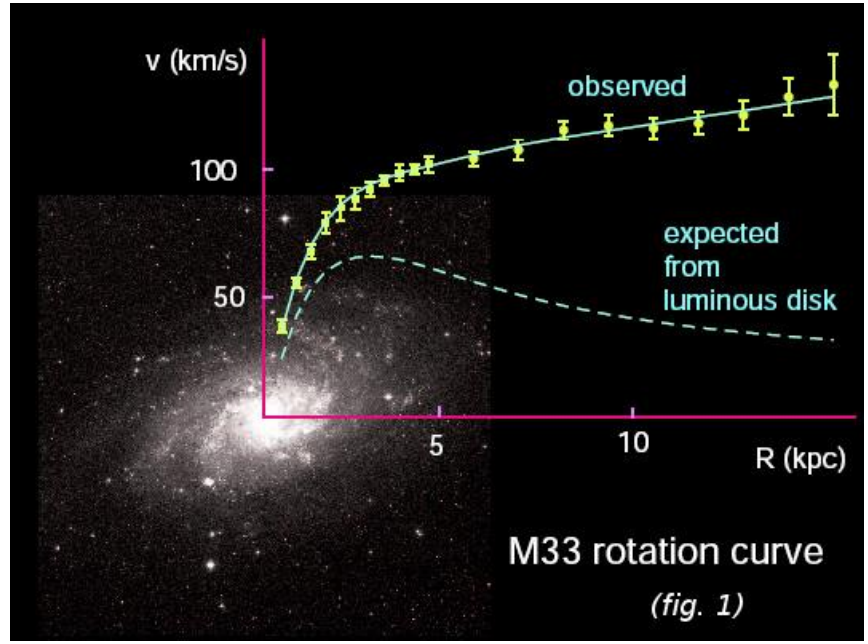
Introduction

Evidence of DM from rotation curve

$$\frac{mv_r^2}{r} = \frac{GM_r m}{r^2}$$



$$v_r \sim \frac{1}{r^{1/2}} \quad \text{(Keplerian Decline)}$$

Missing mass ~ Non-baryonic

Evidence of DM in bullet cluster

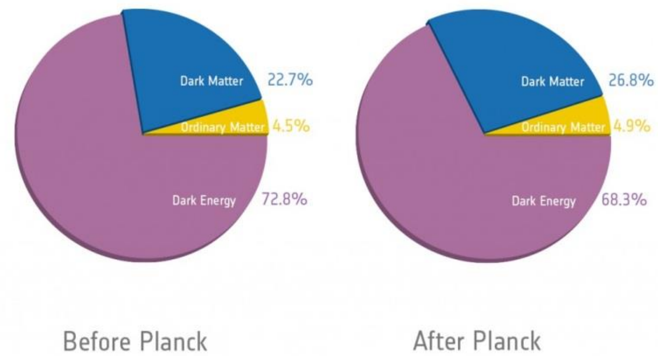
(Collision of galaxies in Bullet cluster1E 0657-56)

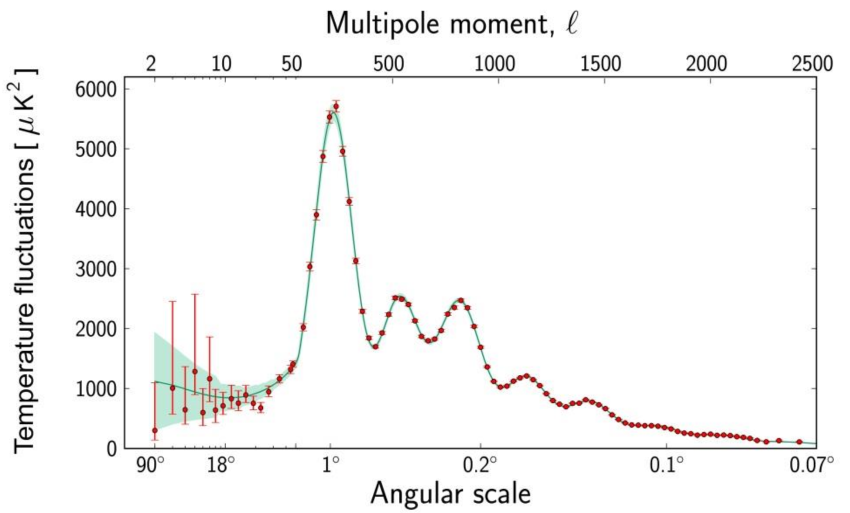
(Blue color) Dark matter seen through gravitational lensing and is found to be 7 times larger than baryonic mass.

Markevitch et.al, Astro Phy J, 2004

(Pink color) Hot gas seen through X-ray by Chandra X-ray observatory at the central part

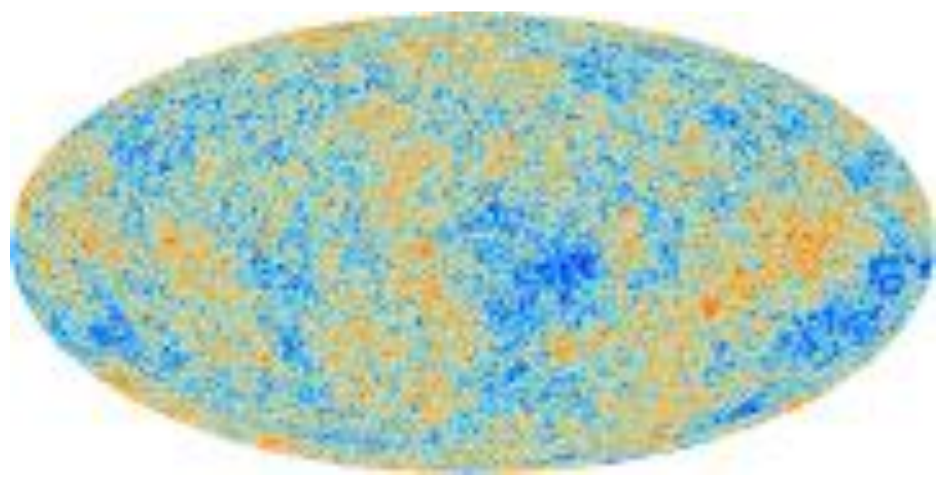
Evidence of DM in CMB





@WMAP(Wilkinson Microwave Anisotropy Probe)

@ PLANCK 2013



Nature of Dark Matter…

From the astrophysical evidences of dark matter one infers that…

- ✓ DM should be a massive particle and hence interact gravitationally.
- ✓ It is electrically neutral and colorless. Therefore it could hide itself easily.
- ✓ It is stable on the cosmological time scale and therefore the large scale structure exists.

However,
We don't know …

Mass of DM= ?
Spin of DM= ?, Charge of DM= ?
Interaction apart from gravity ?
Relic abundance (symmetric/asymmetric ?)

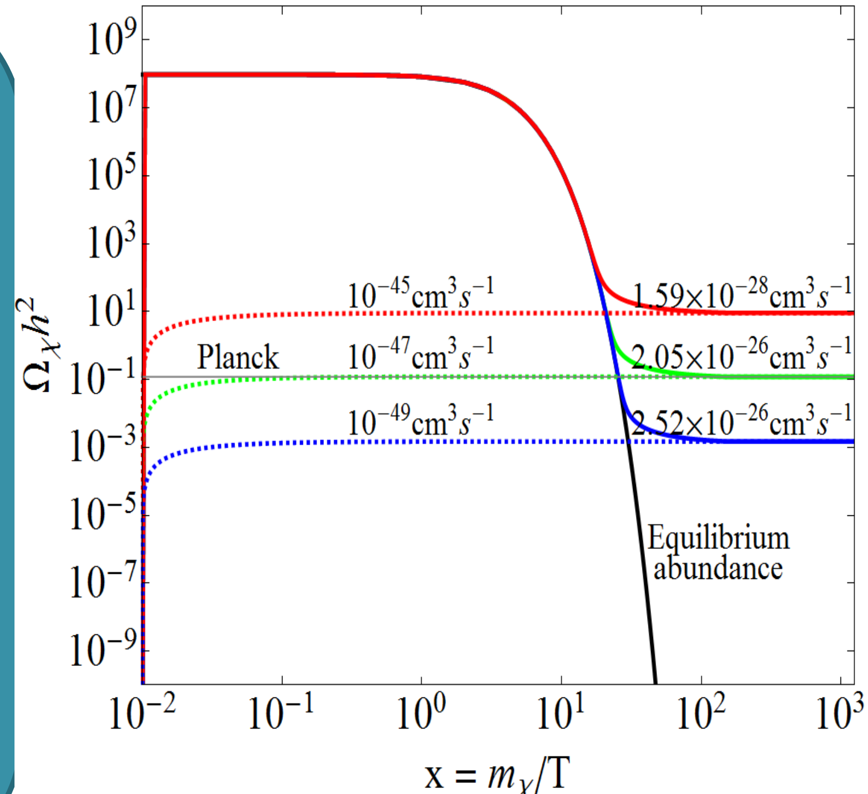
→ Many unanswered questions!

Q. How to probe the DM at terrestrial laboratories, which is required for the existence of our Universe ?

Is DM a WIMP (Gravity+ weak) ?

The DM is assumed to be in equilibrium in the early Universe via the weak interaction processes. As the temperature, due to expansion of the Universe, falls below the mass scale of DM, the latter gets freeze-out from the thermal bath and gives the correct relic abundance.

Steigman and Turner, 1984



$$\frac{dY_\chi}{dx} = \frac{-x\langle\sigma|v|\rangle s}{H(m_\chi)}(Y_\chi{}^2 - Y_{eq}{}^2)$$

$$Y_\chi = \frac{n_\chi}{s}, x = \frac{m_\chi}{T}$$

$$\Omega_{DM}h^2 = \frac{1.1\times 10^9 \, GeV^{-1} x_F}{g_*^{1/2} M_{pl} \langle \sigma |v| \rangle_F} = 0.1198 \pm 0.0026$$

Analytical estimation of a WIMP relic density

The observed relic abundance of DM by WMAP and PLANCK

$$<\sigma |v| >|_F \approx 3\times 10^{-26} cm^3 / \sec \approx 2.6\times 10^{-9} GeV^{-2}$$

$$\approx O(10^{-36}) cm^2$$

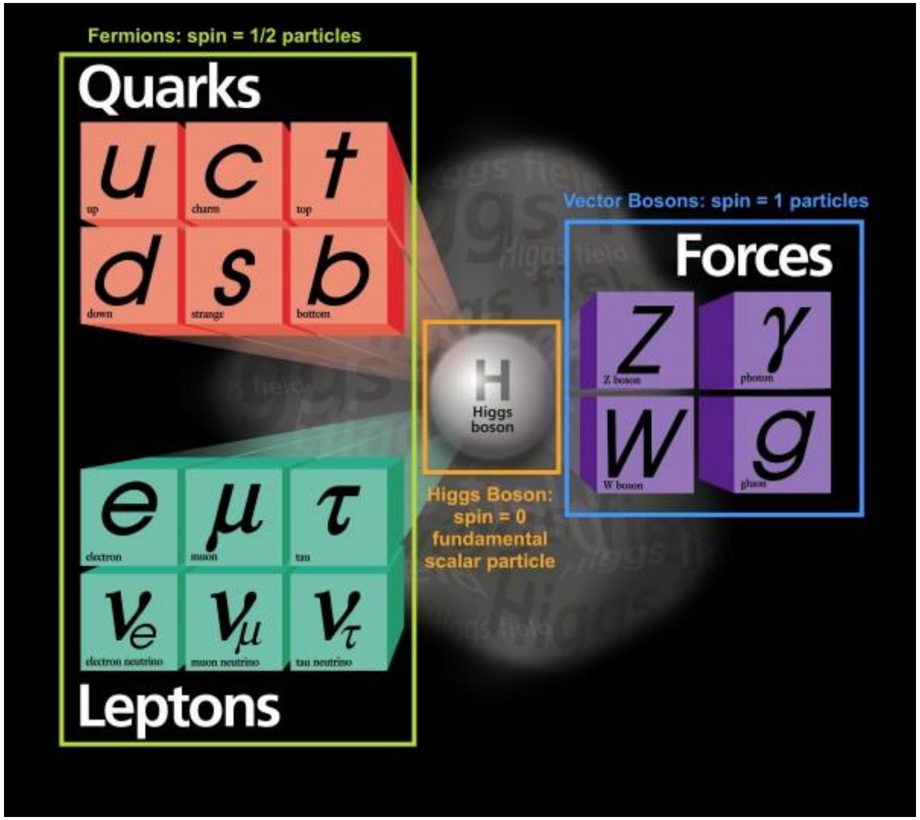
Which is typically a weak interaction cross-section.

WIMP Miracle

Therefore one believes that DM could be a WIMP.

Dark matter:
Physics beyond the SM ?

DM: The physics beyond the SM



The only particles in SM which seem to satisfy some properties of DM are neutrinos:

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{91.5eV} \approx 0.0024$$

$$<< \Omega_{DM} h^2$$

Cowsik and McClelland, PRL 1972

So, we need to look for a candidate of DM in the beyond standard model of particle physics, which is probably heavy (> a few GeV).

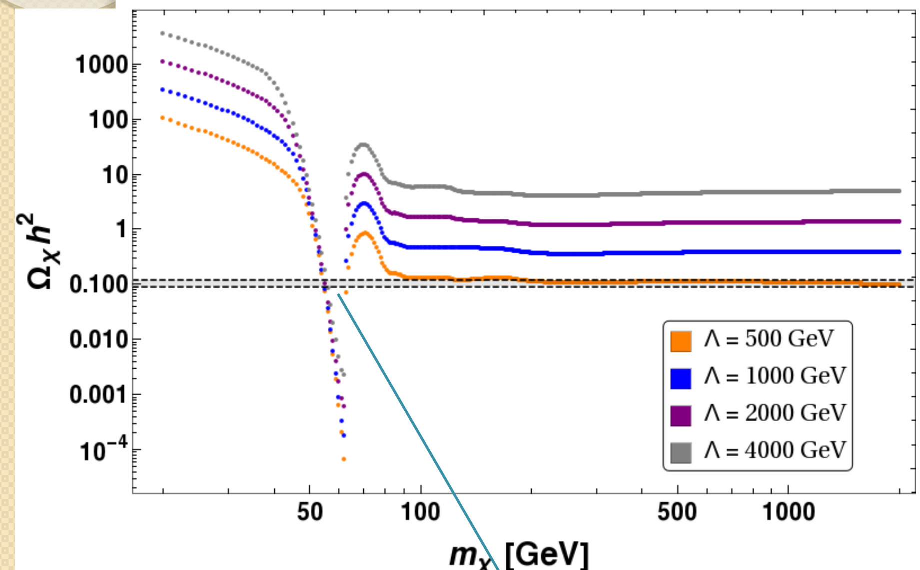
Lee and Weinberg, PRL 1977

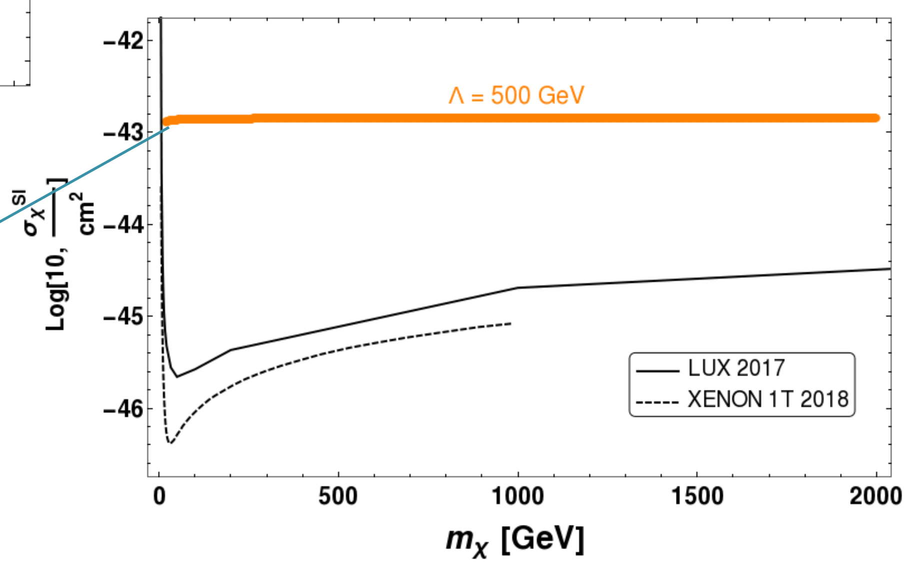
Vector-like fermions as DM candidates in BSM scenarios

(1) S. Bhattacharya, Nirakar Sahoo and **N. Sahu**, PRD93, 2016
(2) S. Bhattacharya, S Patra, Nirakar Sahoo, **N.Sahu**, JCAP 1606, 2016
(3) S. Bhattacharya, Nirakar Sahoo and **N. Sahu**, PRD96, 2017
(4) S. Bhattacharya, Purusottam Ghosh, Nirakar Sahoo and **N. Sahu**, 1812.06505 (Front.in Phys.7 (2019)
(5) B. Barman, S. Bhattacharya, P. Ghosh, S. Kadam and **N. Sahu,** 1902.01217 (PRD 100, 2019)

Vector-like singlet fermion DM

$$\mathcal{L}_{DM} = \bar{\chi}(i\gamma^\mu\partial_\mu - m_\chi)\chi - \frac{1}{\Lambda}(H^\dagger H - \frac{v^2}{2})\bar{\chi}\,\chi$$





Allowed zone
of valid DM

Inert lepton doublet (ILD) DM

The Lagrangian of the model is given as:

$$\mathcal{L}^{IL} = \overline{N}\left[i\gamma^\mu\left(\partial_\mu - ig\frac{\sigma^a}{2}W^a_\mu - ig'\frac{Y}{2}B_\mu\right) - m_N\right]N. \quad (2)$$

$$N = \begin{pmatrix} N^0 \\ N^- \end{pmatrix}$$

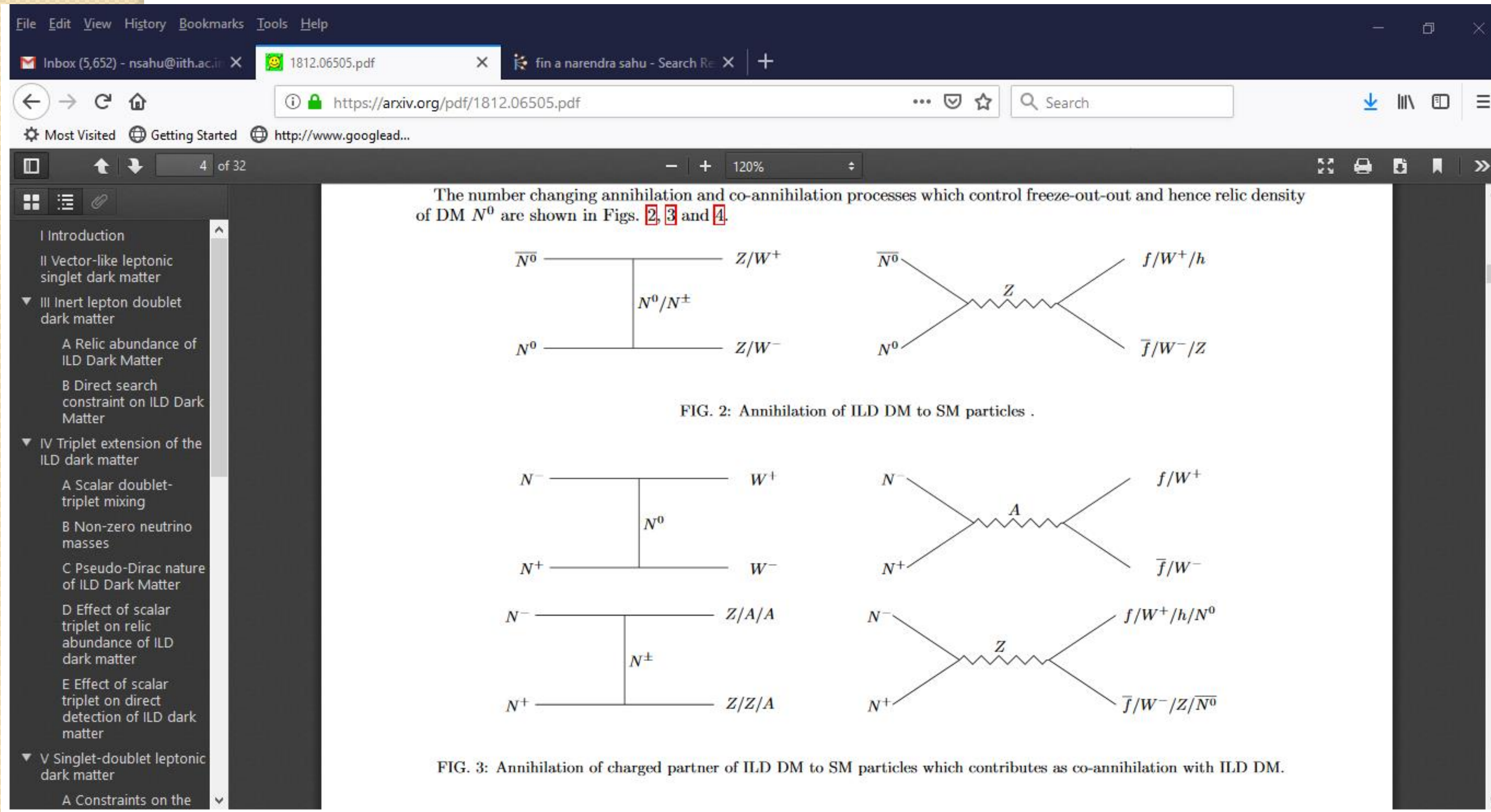
Thus the only new parameter introduced in the above Lagrangian is the mass of N, *i.e.* m_N. Expanding the covariant derivative of the above Lagrangian $\mathcal{L}^{IL}$, we get the interaction terms of N^0 and $N^\pm$ with the SM gauge bosons as:

$$\begin{aligned}\mathcal{L}^{IL}_{int} &= \overline{N}i\gamma^\mu\left(-ig\frac{\sigma^a}{2}W^a_\mu + i\frac{g'}{2}B_\mu\right)N \\ &= \left(\frac{e_0}{2\sin\theta_W\cos\theta_W}\right)\overline{N^0}\gamma^\mu Z_\mu N^0 + \frac{e_0}{\sqrt{2}\sin\theta_W}\overline{N^0}\gamma^\mu W^+_\mu N^- + \frac{e_0}{\sqrt{2}\sin\theta_W}N^+\gamma^\mu W^-_\mu N^0 \\ &\quad - e_0 N^+\gamma^\mu A_\mu N^- - \left(\frac{e_0}{2\sin\theta_W\cos\theta_W}\right)\cos 2\theta_W N^+\gamma^\mu Z_\mu N^-. \end{aligned} \quad (3)$$

where $g = e_0/\sin\theta_W$ and $g' = e_0/\cos\theta_W$ with e_0 being the electromagnetic coupling constant and θ_W being the Weinberg angle.

Since N is a doublet under $SU(2)_L$, it can contribute to invisible Z-decay width if its mass is less than 45 GeV which is strongly constrained. Therefore, in our analysis we will assume $m_N > 45$ GeV.

A. Relic abundance of ILD Dark Matter



The number changing annihilation and co-annihilation processes which control freeze-out-out and hence relic density of DM N^0 are shown in Figs. 2, 3 and 4.

FIG. 2: Annihilation of ILD DM to SM particles .

FIG. 3: Annihilation of charged partner of ILD DM to SM particles which contributes as co-annihilation with ILD DM.

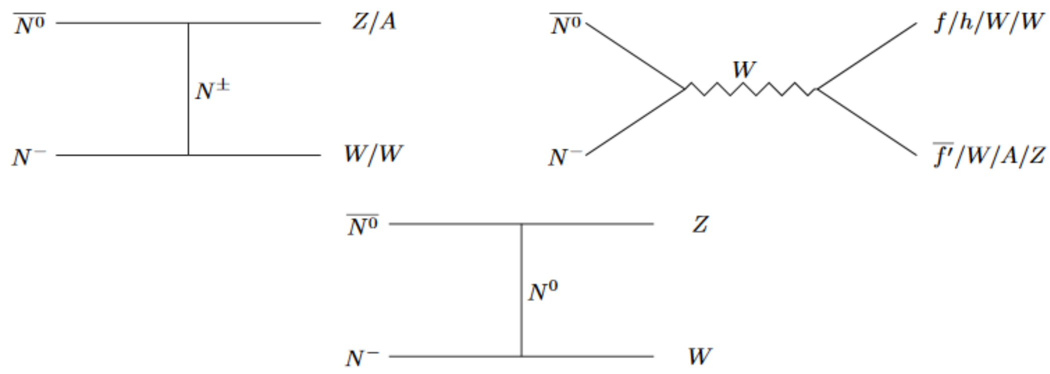
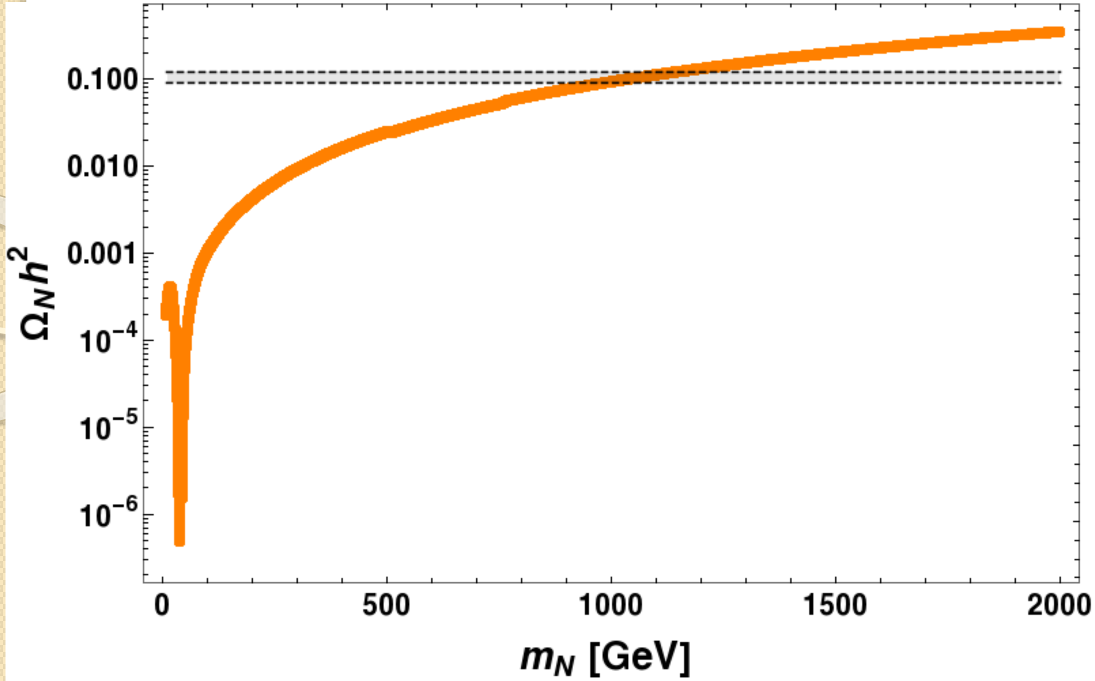
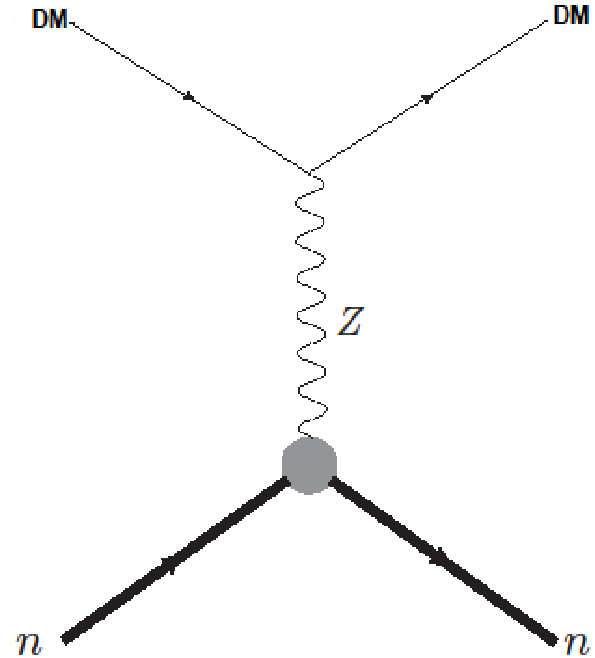


FIG. 4: Co-annihilation processes of DM N^0 with its charged partner $N^{\pm}$ to SM particles.

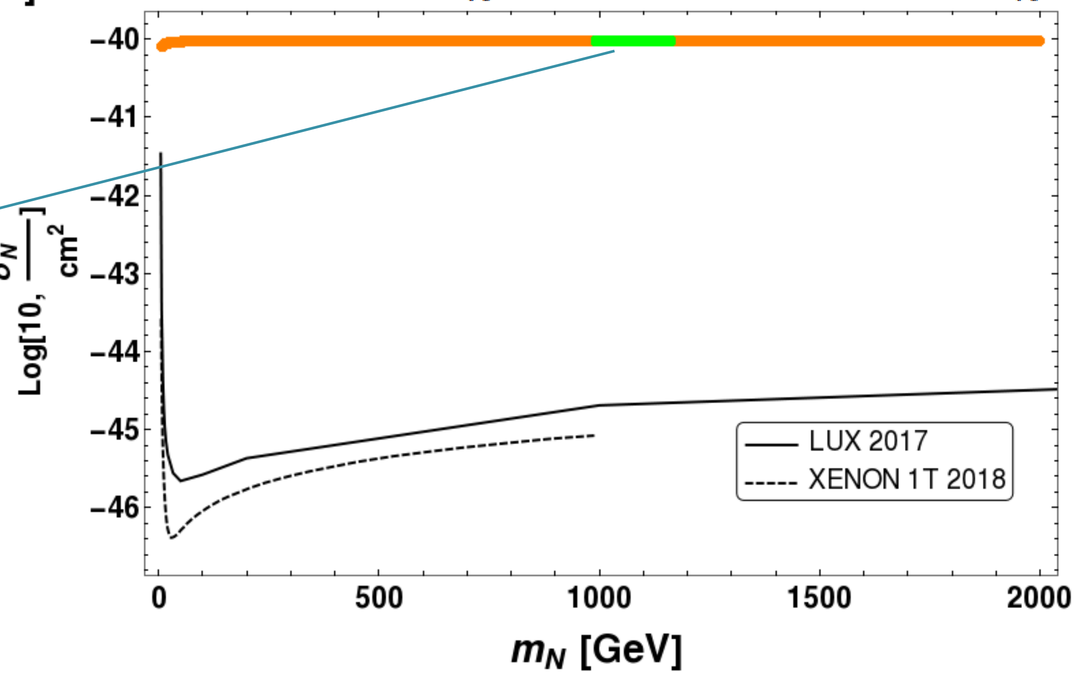
To estimate the relic density of DM of this framework one needs to solve the relevant Boltzmann equation which can be given as:

$$\frac{dn_{N^0}}{dt} + 3Hn_{N^0} = -\langle\sigma v\rangle_{N^0\overline{N^0}\to SMSM}\left(n_{N^0}^2 - {n_{N^0}^{eq}}^2\right) - \langle\sigma v\rangle_{N^0N^{\pm}\to SMSM}\left(n_{N^0}n_{N^{\pm}} - n_{N^0}^{eq}n_{N^{\pm}}^{eq}\right). \quad (4)$$

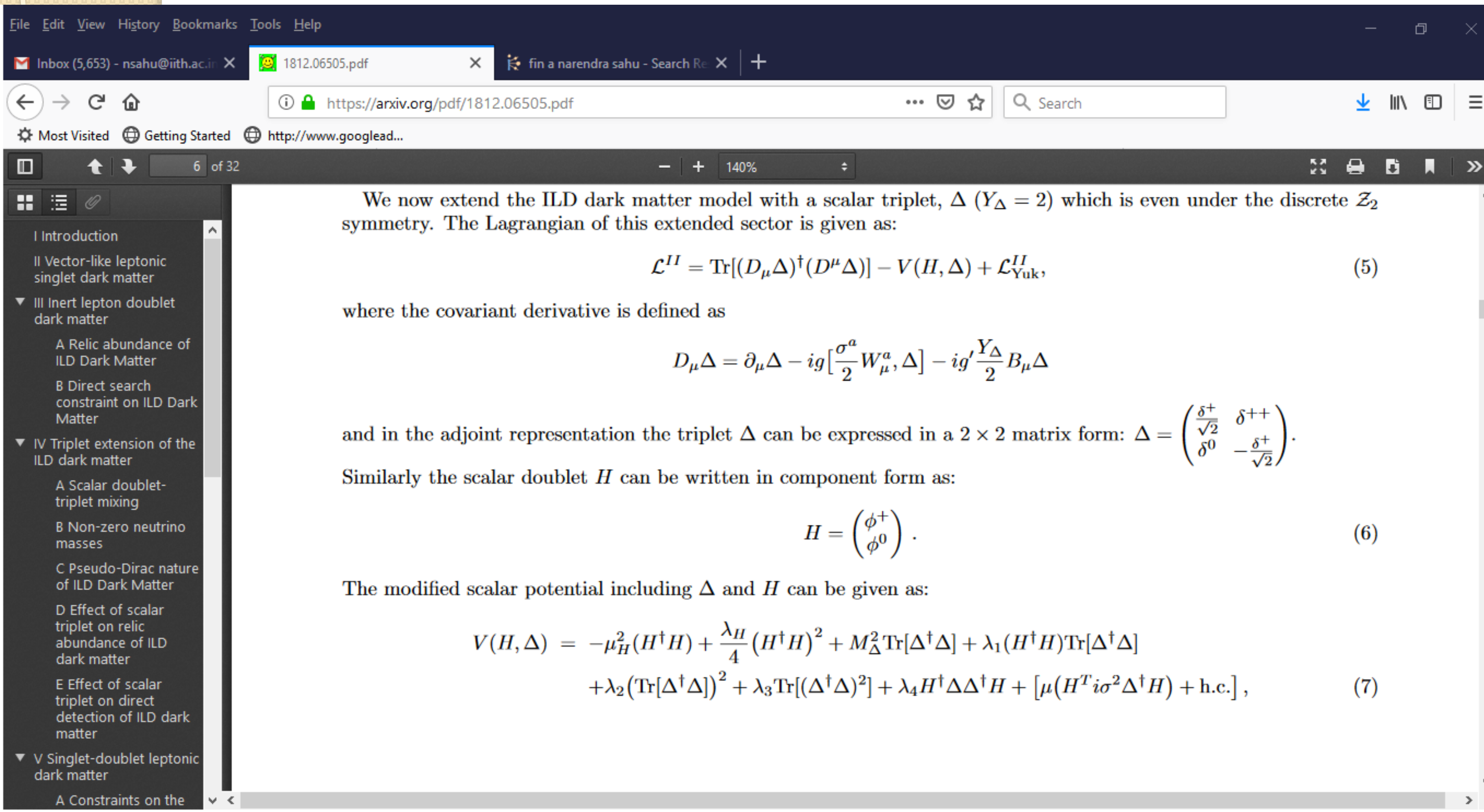




Inert lepton doublet DM alone is ruled out by direct search



Scalar triplet extension of ILD DM



We now extend the ILD dark matter model with a scalar triplet, Δ ($Y_\Delta = 2$) which is even under the discrete $\mathcal{Z}_2$ symmetry. The Lagrangian of this extended sector is given as:

$$\mathcal{L}^{II} = \mathrm{Tr}[(D_\mu\Delta)^\dagger(D^\mu\Delta)] - V(H,\Delta) + \mathcal{L}^{II}_{\mathrm{Yuk}}, \tag{5}$$

where the covariant derivative is defined as

$$D_\mu\Delta = \partial_\mu\Delta - ig[\frac{\sigma^a}{2}W^a_\mu, \Delta] - ig'\frac{Y_\Delta}{2}B_\mu\Delta$$

and in the adjoint representation the triplet Δ can be expressed in a 2×2 matrix form: $\Delta = \begin{pmatrix} \frac{\delta^+}{\sqrt{2}} & \delta^{++} \\ \delta^0 & -\frac{\delta^+}{\sqrt{2}} \end{pmatrix}$.

Similarly the scalar doublet H can be written in component form as:

$$H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}. \tag{6}$$

The modified scalar potential including Δ and H can be given as:

$$\begin{aligned} V(H,\Delta) &= -\mu_H^2(H^\dagger H) + \frac{\lambda_H}{4}(H^\dagger H)^2 + M_\Delta^2\mathrm{Tr}[\Delta^\dagger\Delta] + \lambda_1(H^\dagger H)\mathrm{Tr}[\Delta^\dagger\Delta] \\ &+\lambda_2(\mathrm{Tr}[\Delta^\dagger\Delta])^2 + \lambda_3\mathrm{Tr}[(\Delta^\dagger\Delta)^2] + \lambda_4 H^\dagger\Delta\Delta^\dagger H + [\mu(H^T i\sigma^2\Delta^\dagger H) + \mathrm{h.c.}], \end{aligned} \tag{7}$$

Where Δ is a scalar triplet and does not acquire any vev. After electroweak phase transition, it acquires a small induced vev.

$$\mathcal{L}_{yuk} = \frac{1}{\sqrt{2}}[(f_L)_{\alpha\beta}\overline{L_\alpha{}^c}i\tau_2\Delta L_\beta + f_N\overline{N^c}i\tau_2\Delta N + h.c.$$

Lepton number violation by two units

Majorana mass of neutrino:

$$M_\nu = f_L < \Delta > = -f_L f_H \frac{v^2}{M_\Delta}$$

A free lunch

$$\rho = \frac{M_W{}^2}{M_Z{}^2 \cos^2\theta_w} = \frac{\frac{g^2}{4}(< H >^2 + 2 < \Delta >^2)}{\frac{g^2 + g'^2}{4\cos^2\theta_w}(< H >^2 + 4 < \Delta >^2)} = 1.00037 \pm 0.00023$$

$$\Rightarrow < \Delta > < 3.64 GeV$$

The scalar triplet also induces a Majorana mass to DM, which does not affect the relic abundance of DM, but it evades the constraints from Z-mediated direct detection. HOW ?

$$-\mathcal{L} = M_N \overline{N^0} N^0 + f_N \overline{(N^0)^c} N^0 \langle \Delta \rangle$$

The Majorana mass splits the DM (Dirac fermion) into two pseudo-Dirac fermions with a small mass splitting:

$$\begin{pmatrix} m & M_N \\ M_N & m \end{pmatrix}$$

$M_N + m \longrightarrow N^0{}_2$

$M_N - m \longrightarrow N^0{}_1$

$$\delta = 2m$$

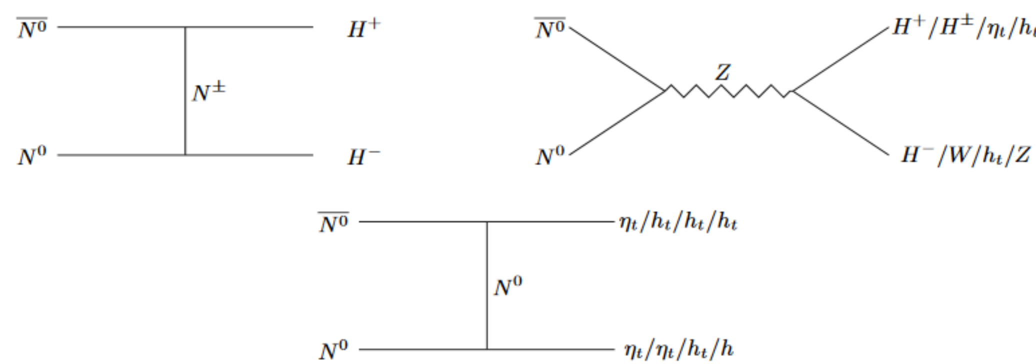
$$= 2 f_N < \Delta > = -2 f_N f_H \frac{v^2}{M_\Delta} = O(MeV - GeV)$$

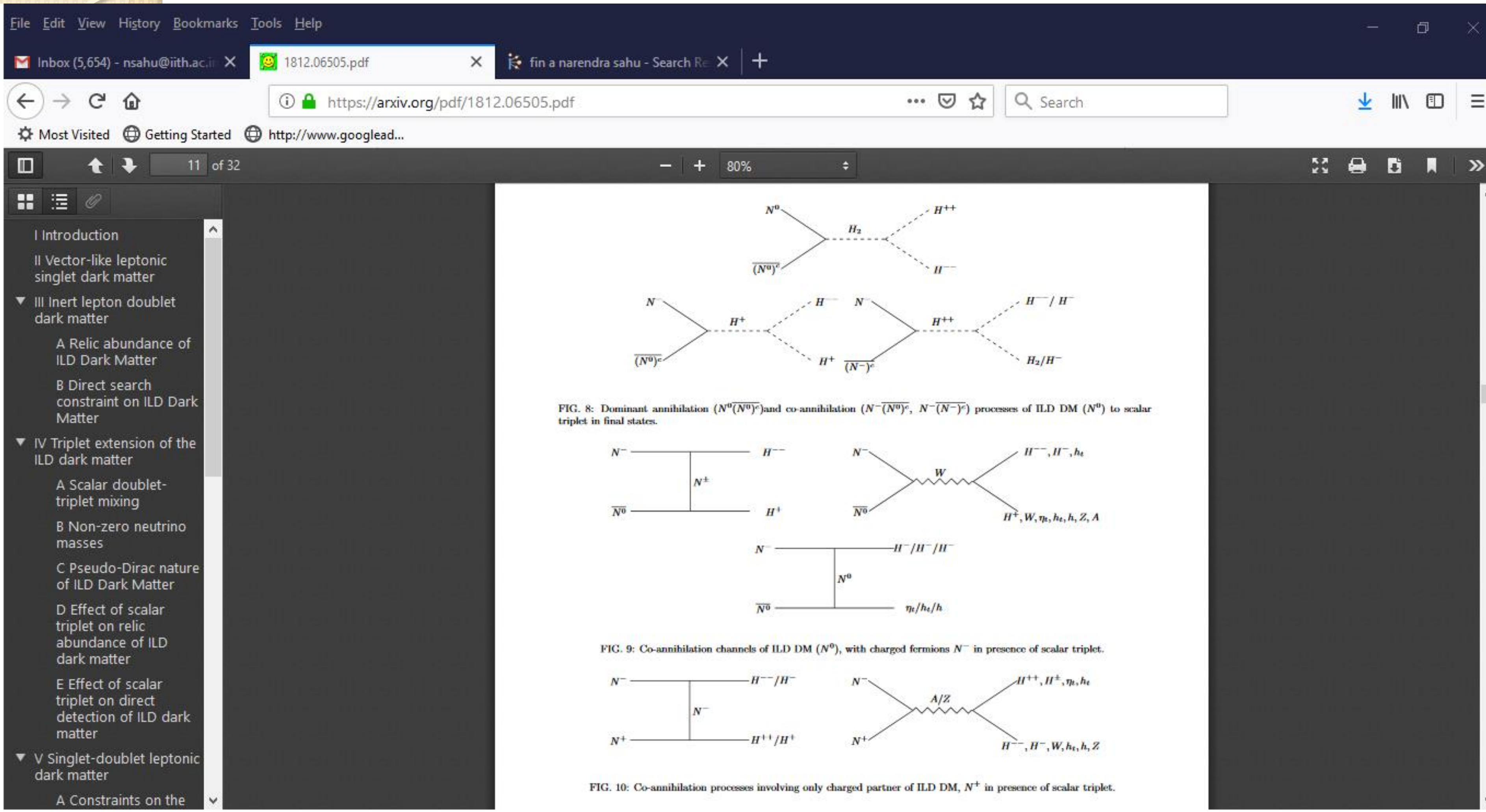
$$R = \frac{M_\nu}{\delta} = \frac{f_L}{f_N} < 10^{-5}$$

This forbids the DM-nucleon scattering via Z-mediated process, which is good for us.

D. Effect of scalar triplet on relic abundance of ILD dark matter

In presence of a scalar triplet, when the DM mass is larger than the triplet mass, a few additional annihilation and co-annihilation channels open up as shown in Figs. 7, 8, 9 and 10 in addition to the previously mentioned Feynman diagrams given in Figs. 2,3 and 4. These additional channels also play a key role in number changing processes of DM, N^0 to yield a modified freeze-out abundance. We numerically calculate relic density of N^0 DM once again by implementing the model in the code **micrOmegas** [24]. The parameter space, in comparison to the ILD dark matter alone, is enhanced due to the additional coupling of N^0 with Δ. In particular, the new parameters are: triplet scalar masses $m_{H_2}, m_{A^0}, m_{H^\pm}, m_{H^{\pm\pm}}$, vev of scalar triplet v_t, coupling of scalar triplet with ILD dark matter N^0, *i.e.* f_N, scalar doublet-triplet mixing $\sin\alpha$.

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III Inert lepton doublet dark matter
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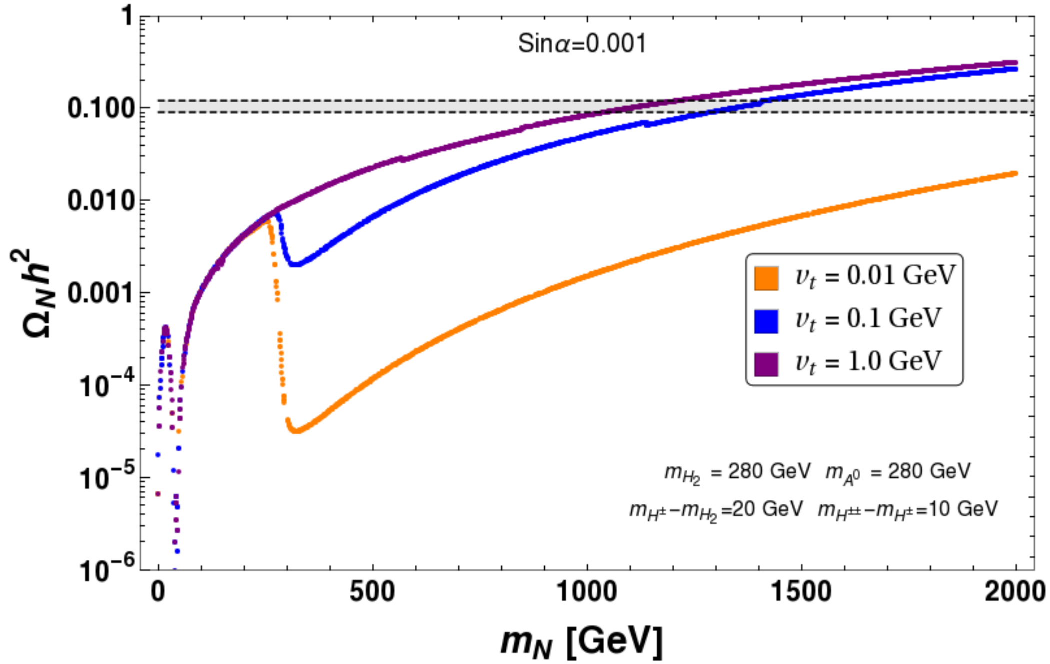
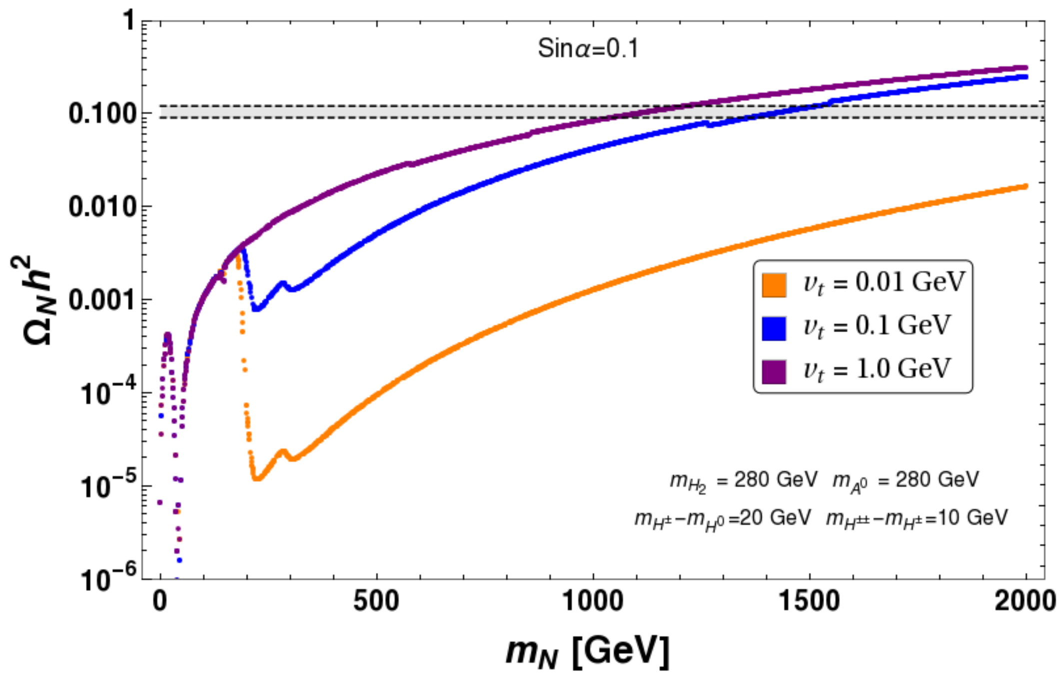
B Non-zero neutrino masses
C Pseudo-Dirac nature of ILD Dark Matter
D Effect of scalar triplet on relic abundance of ILD dark matter
E Effect of scalar triplet on direct detection of ILD dark matter
V Singlet-doublet leptonic dark matter
A Constraints on the
FIG. 8: Dominant annihilation ($N^0\overline{(N^0)^c}$)and co-annihilation ($N^-\overline{(N^0)^c}$, $N^-\overline{(N^-)^c}$) processes of ILD DM (N^0) to scalar triplet in final states.
FIG. 9: Co-annihilation channels of ILD DM (N^0), with charged fermions N^- in presence of scalar triplet.
FIG. 10: Co-annihilation processes involving only charged partner of ILD DM, N^+ in presence of scalar triplet.


Sinα=0.001
vt = 0.01 GeV
vt = 0.1 GeV
vt = 1.0 GeV
mH2 = 280 GeV mA0 = 280 GeV
mH± − mH2 =20 GeV mH±± − mH± =10 GeV
ΩN h2
mN [GeV]
1
0.100
0.010
0.001
10−4
10−5
10−6
0
500
1000
1500
2000


Sinα=0.1
vt = 0.01 GeV
vt = 0.1 GeV
vt = 1.0 GeV
mH2 = 280 GeV mA0 = 280 GeV
mH± − mH0 =20 GeV mH±± − mH± =10 GeV
ΩN h2
mN [GeV]
1
0.100
0.010
0.001
10−4
10−5
10−6
0
500
1000
1500
2000

Effect of scalar triplet on direct detection of ILD dark matter

E. Effect of scalar triplet on direct detection of ILD dark matter

As discussed in section III B, the ILD dark matter alone is ruled out due to large Z-mediated elastic scattering with nucleus. However, it can be reinstated in presence of the scalar triplet, which not only forbids the Z-mediated elastic scattering [23] but also provides a new portal for the detection of ILD dark matter via the doublet-triplet mixing as we discuss below.

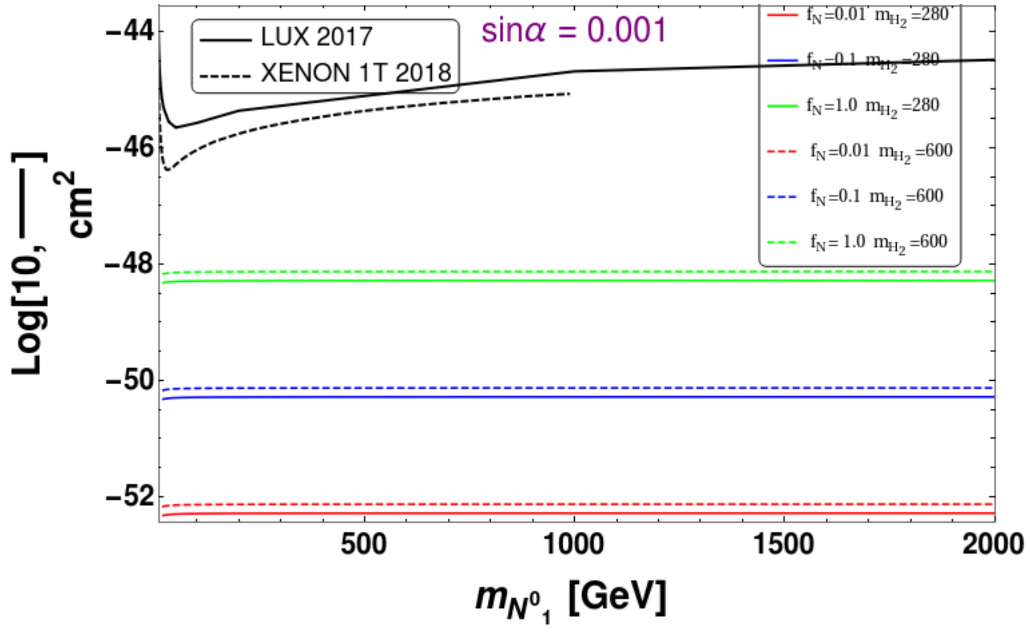
The interaction of DM with the Z boson with the kinetic term is given as

$$\mathcal{L}_{Z-DM} \supset i\bar{N}^0\left(\gamma^\mu\partial_\mu - i g_Z \gamma^\mu Z_\mu\right) N^0 \,, \tag{33}$$

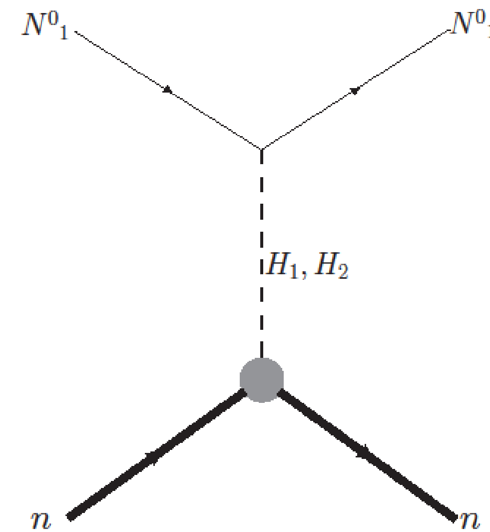
where $ig_Z = \frac{g}{2\cos\theta_W}$. After the symmetry breaking the scalar triplet Δ gets an induced vev and hence gives Majorana mass to the ILD dark matter N_0 as shown in eq. 29. The presence of such Majorana mass term splits the Dirac DM state into two real Majorana states N_1^0 and N_2^0 with a mass splitting of δm as discussed in sec IV C. Now we rewrite the Lagrangian involving DM-Z interaction in terms of the new Majorana states as:

$$\mathcal{L}_{\mathrm{Z-DM}} \supset \overline{N_1^0} i\gamma^\mu\partial_\mu N_1^0 + \overline{N_2^0} i\gamma^\mu\partial_\mu N_2^0 - i g_z \overline{N_1^0}\gamma^\mu N_2^0 Z_\mu \,. \tag{34}$$

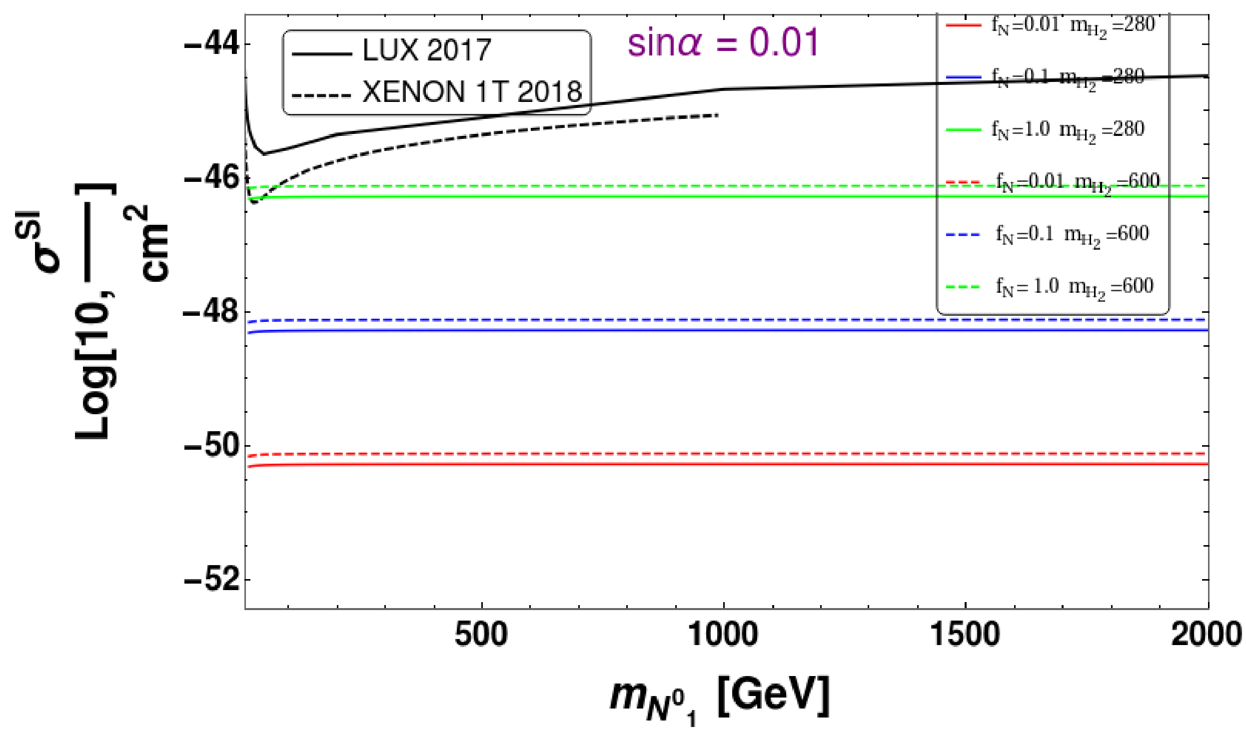
We can see that the dominant gauge interaction becomes off-diagonal. The absence of diagonal interaction term for the DM-Z vertex leads to the vanishing contribution to elastic scattering of the DM with the nucleus. However there could be an inelastic scattering through Z mediation, which is suppressed if the mass splitting between two states is of the order $\mathcal{O}(100)$ keV or less. But the Yukawa term involving DM and Δ is still diagonal in the new basis and hence can lead to elastic scattering through a mixing between the doublet-triplet Higgs. Assuming N_1^0 to be the



LUX 2017
XENON 1T 2018
sinα = 0.001
fN=0.01 mH2 =280
fN=0.1 mH2 =280
fN=1.0 mH2 =280
fN=0.01 mH2 =600
fN=0.1 mH2 =600
fN= 1.0 mH2 =600
-44
-46
-48
-50
-52
500
1000
1500
2000
Log[10, σSI/cm2]
mN01 [GeV]



N01
N01
H1, H2
n
n



LUX 2017
XENON 1T 2018
sinα = 0.01
fN=0.01 mH2 =280
fN=0.1 mH2 =280
fN=1.0 mH2 =280
fN=0.01 mH2 =600
fN=0.1 mH2 =600
fN= 1.0 mH2 =600
-44
-46
-48
-50
-52
500
1000
1500
2000
Log[10, σSI/cm2]
mN01 [GeV]

Thus the scalar triplet reinstate the ILD dark matter by splitting the Dirac fermion into two pseudo-Dirac states. However, it can not reduce the mass of DM to below TeV scales. Therefore, a complementary search of ILD dark matter at collider lacks any signal.

Singlet-Doublet mixed Fermion DM

We overcome the problem of small relic abundance by introducing a vector-like singlet fermion χ^0, which mixes with the neutral component of the doublet fermion and decreases the annihilation cross-section. As a result we get the correct relic abundance.

$$\mathcal{L}_{DM} = M_N \overline{N} N + M_\chi \overline{\chi^0} \chi^0 + [Y \overline{N} \tilde{H} \chi^0 + h.c.]$$
$$+ \overline{N} i\gamma^\mu D_\mu N + \overline{\chi^0} i\gamma^\mu \partial_\mu \chi^0$$

where $$N = \begin{pmatrix} N^0 \\ N^- \end{pmatrix} \equiv (1,2,-1), H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \equiv (1,2,1), \chi^0 \equiv (1,1,0)$$

For various purpose see: hep-th/0501082, hep-ph/0510064, arXiv: 0705.4493, arXiv:0706.0918, arXiv:0804.4080, arXiv: 1404.4398 arXiv:1109.2604, arXiv:1311.5896, arXiv:1504.07892, arXiv:1505.03867

Singlet-Doublet mixed Fermion DM

Under Z_2 symmetry both χ^0 and N are odd. As a result the DM emerges as a mixture of singlet fermion χ^0 and the neutral component of the vector-like doublet fermion N.

After EW phase transition the mass matrix for neutral vector-like fermions is given by

$$\begin{pmatrix} \overline{N^0} & \overline{\chi^0} \end{pmatrix} \begin{pmatrix} M_N & m_D \\ m_D & M_\chi \end{pmatrix} \begin{pmatrix} N^0 \\ \chi^0 \end{pmatrix}$$

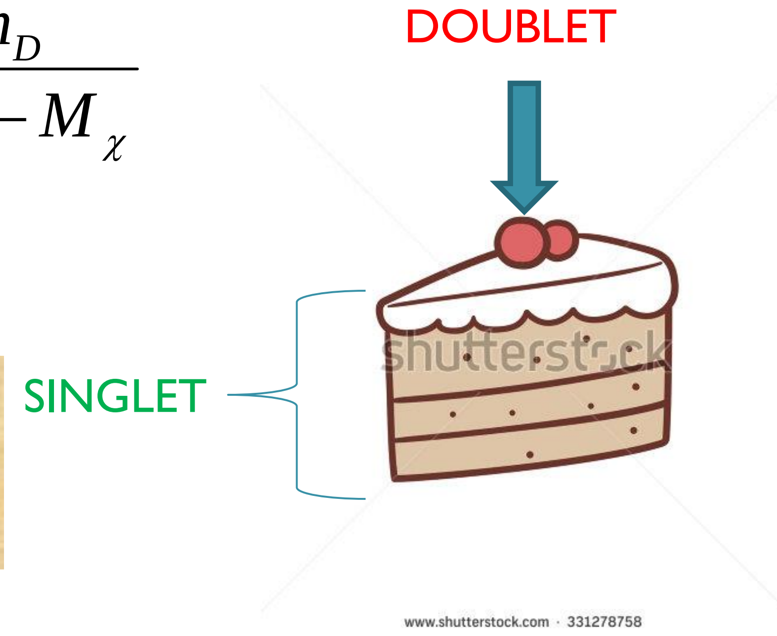
Where $m_D = Y < H >$

$$M_1 = M_\chi - \frac{m_D^2}{M_N - M_\chi}; N_1 = \cos\theta\chi^0 + \sin\theta N^0$$

$$M_2 = M_N + \frac{m_D^2}{M_N - M_\chi}; N_2 = \cos\theta N^0 - \sin\theta\chi^0$$

$$M^\pm = M_1 \sin^2\theta + M_2 \cos^2\theta = M_N; N^\pm$$

$$\tan 2\theta = \frac{m_D}{M_N - M_\chi}$$



The lightest particle is the N_1, which is candidate of dark matter with appropriate mixing angle θ

$sin\theta \leq 0.1$ → From exclusion of direct detection of dark matter

$\sin\theta \geq O(10^{-5})$ → NLSP decay before the DM freezes out, so that no over production of dark matter

We will scan the parameter space within the the given range of singlet-doublet mixing:

$$10^{-5} < \sin\theta < 0.1$$

Relic density of mixed Fermion DM

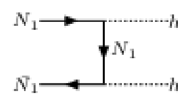
$$\Omega_{N_1} h^2 = \frac{1.09\times 10^9}{g_*^{1/2}(M_{pl}/GeV)}\frac{1}{J(x_f)}$$

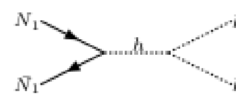
$$J(x_f) = \int_{x_f}^{\infty} \frac{\langle \sigma |v| \rangle_{eff}}{x^2} dx$$

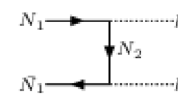
Griest and Secklel: PRD 1991

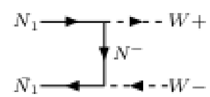
Annihilation processes

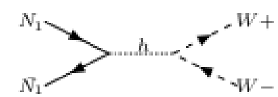
$$N_1 \overline{N_1} \rightarrow SM$$

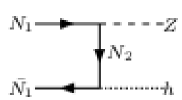


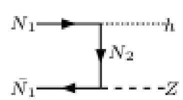


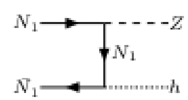


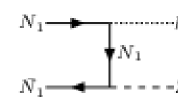


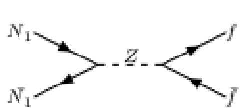


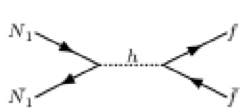


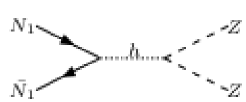


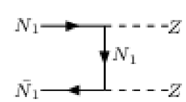


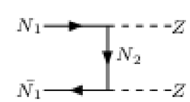






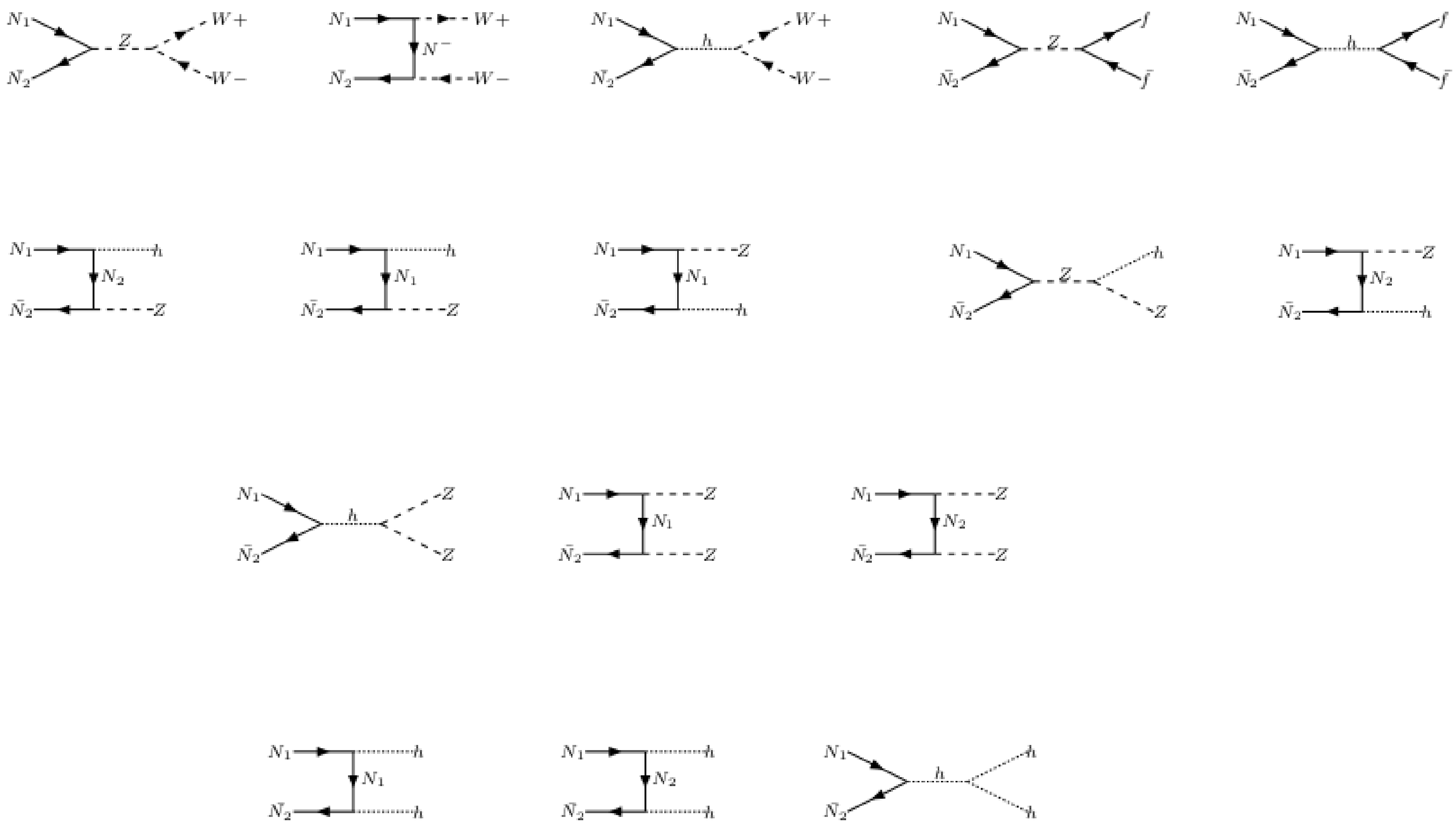






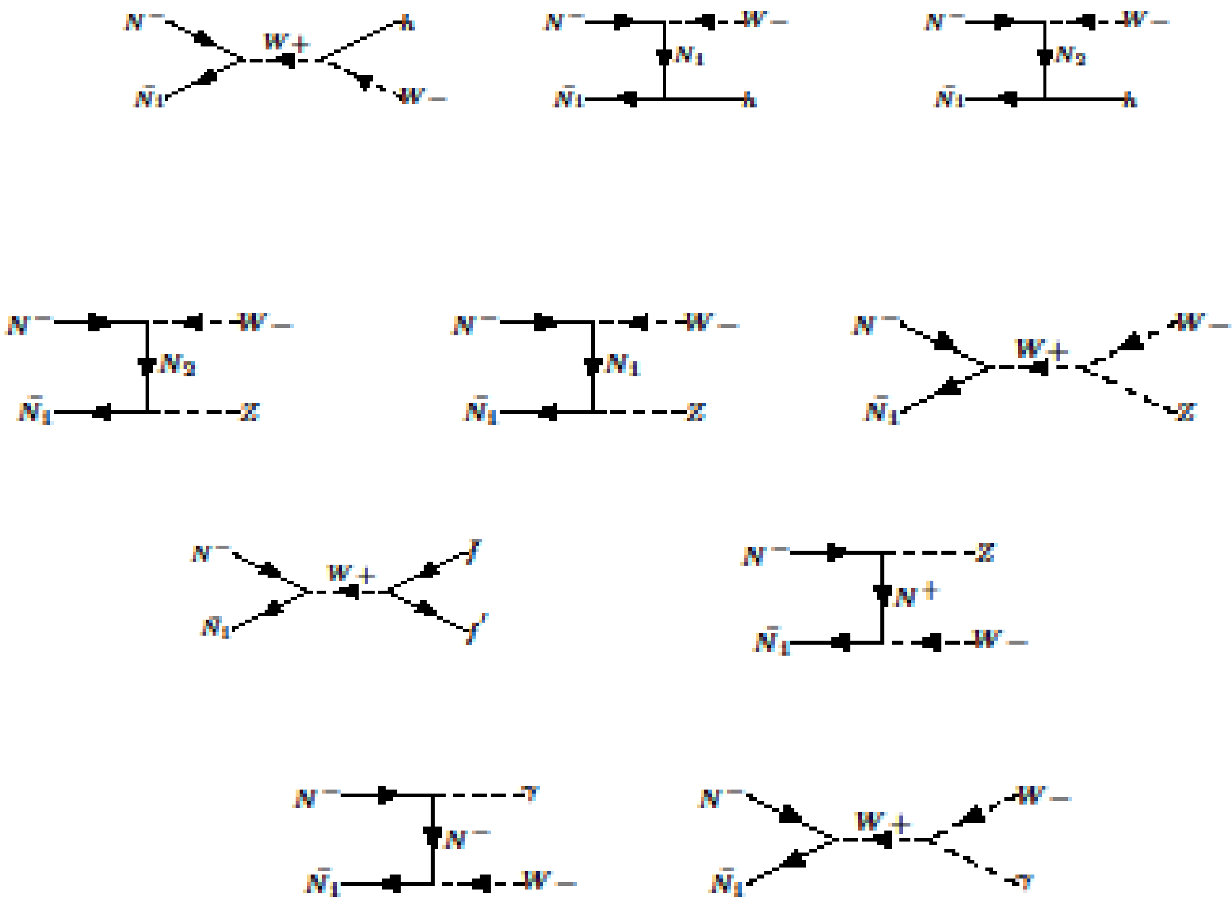
Co-annihilation process

$$N_1 N_2 \to SM$$



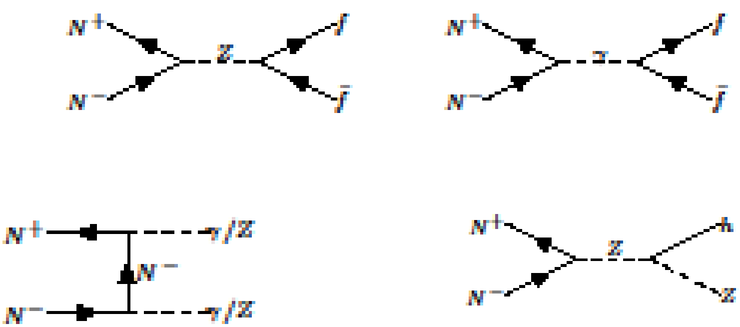
Co-annihilation process

$$N_1 N^- \rightarrow SM$$

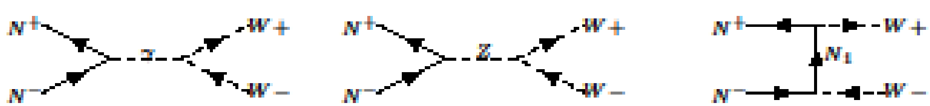


Co-annihilation process

$$N^+ N^- \to SM$$



Note: These diagrams don't depend on singlet-doublet mixing. So in the small mixing limit these diagrams give relic abundance of dark matter.

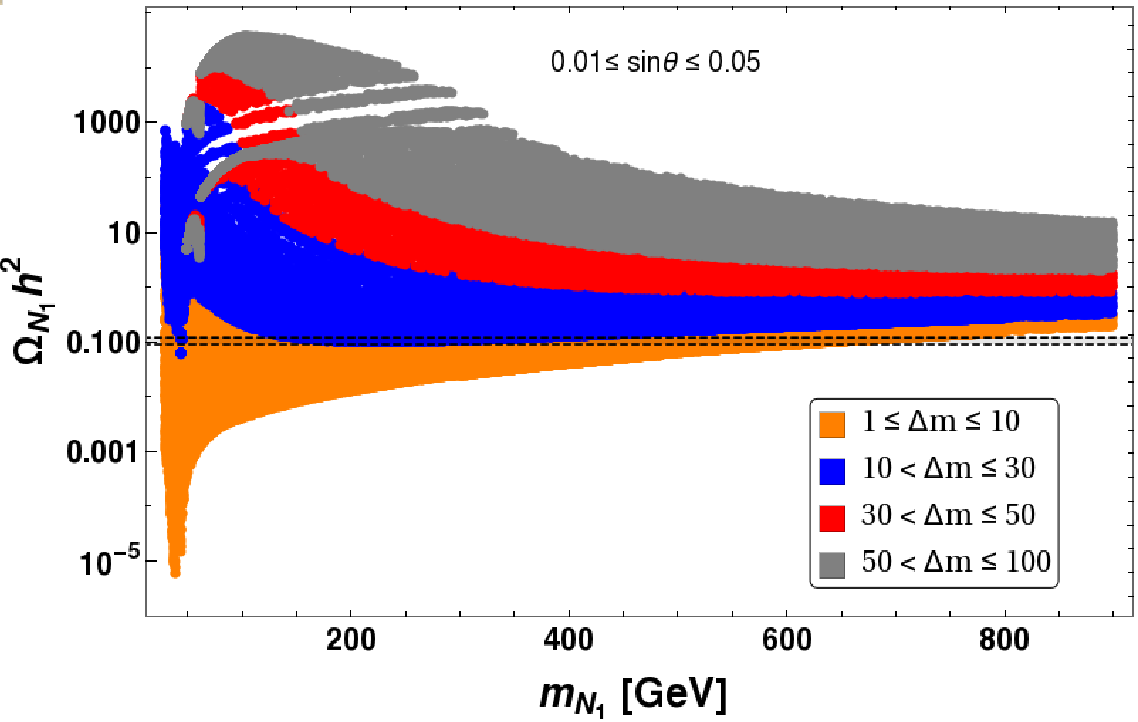


Note: There are many additional channels in presence of the scalar triplet, which we have not drawn here.

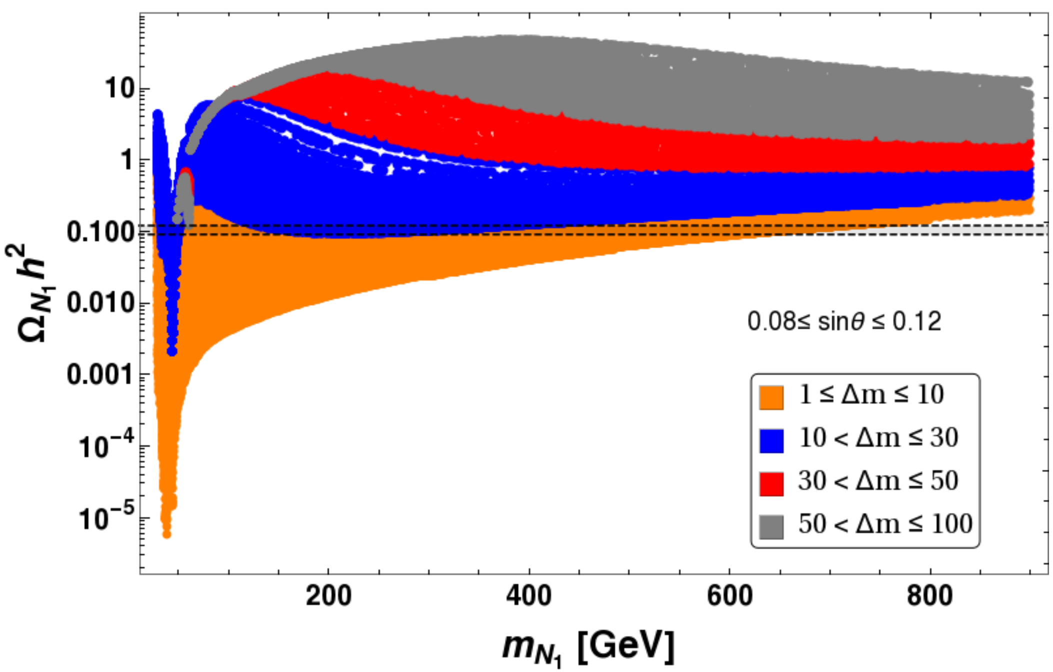
We look for the observed relic abundance in the parameter space spanned by

$$M_1, M_2 \approx M^{\pm}, \sin\theta$$

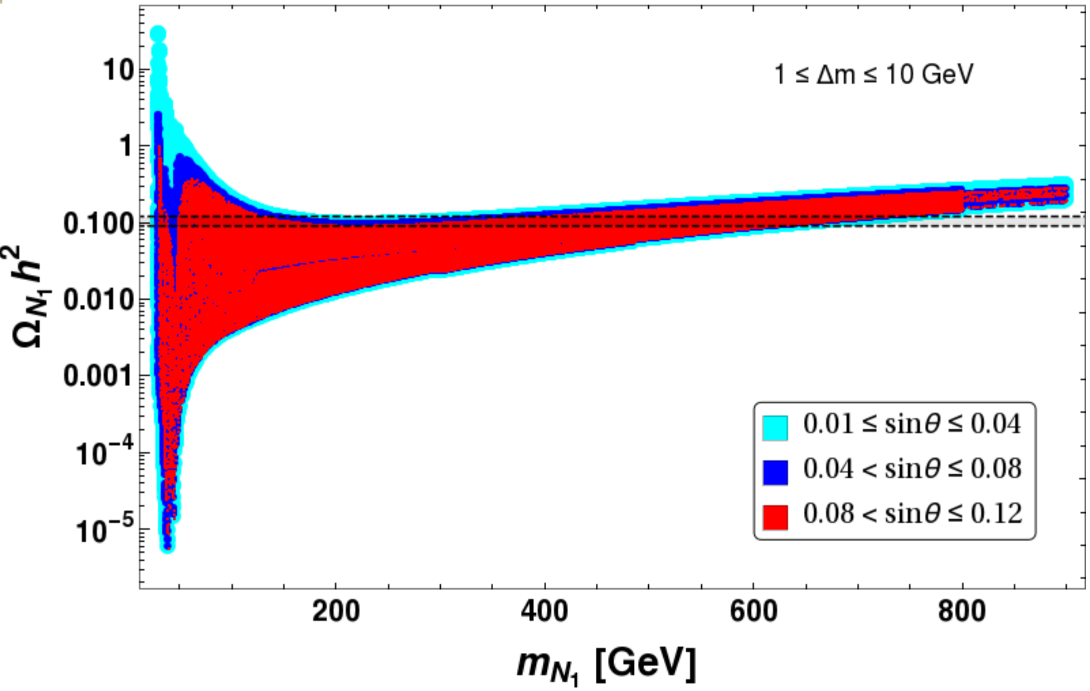
$$Y = \frac{\Delta M \sin 2\theta}{2v}$$



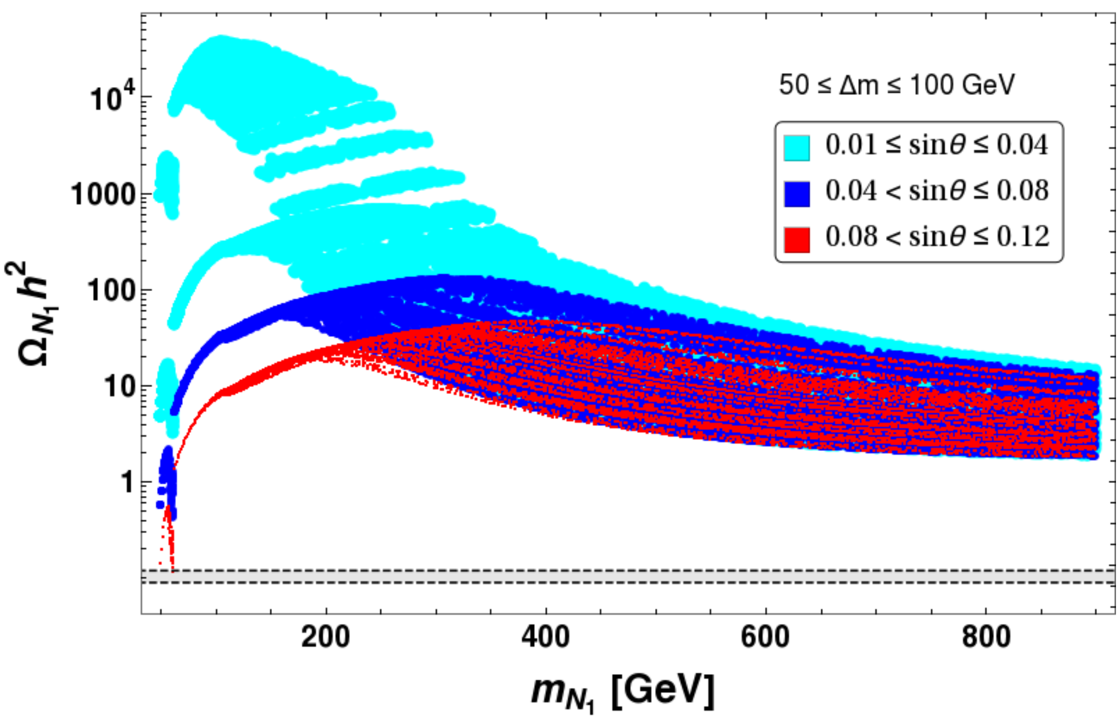
0.01≤ sinθ ≤ 0.05
1000
10
0.100
0.001
10^{-5}
$\Omega_{N_1}h^2$
200
400
600
800
m_{N_1} [GeV]
1 ≤ Δm ≤ 10
10 < Δm ≤ 30
30 < Δm ≤ 50
50 < Δm ≤ 100



10
1
0.100
0.010
0.001
10^{-4}
10^{-5}
$\Omega_{N_1}h^2$
0.08≤ sinθ ≤ 0.12
200
400
600
800
m_{N_1} [GeV]
1 ≤ Δm ≤ 10
10 < Δm ≤ 30
30 < Δm ≤ 50
50 < Δm ≤ 100

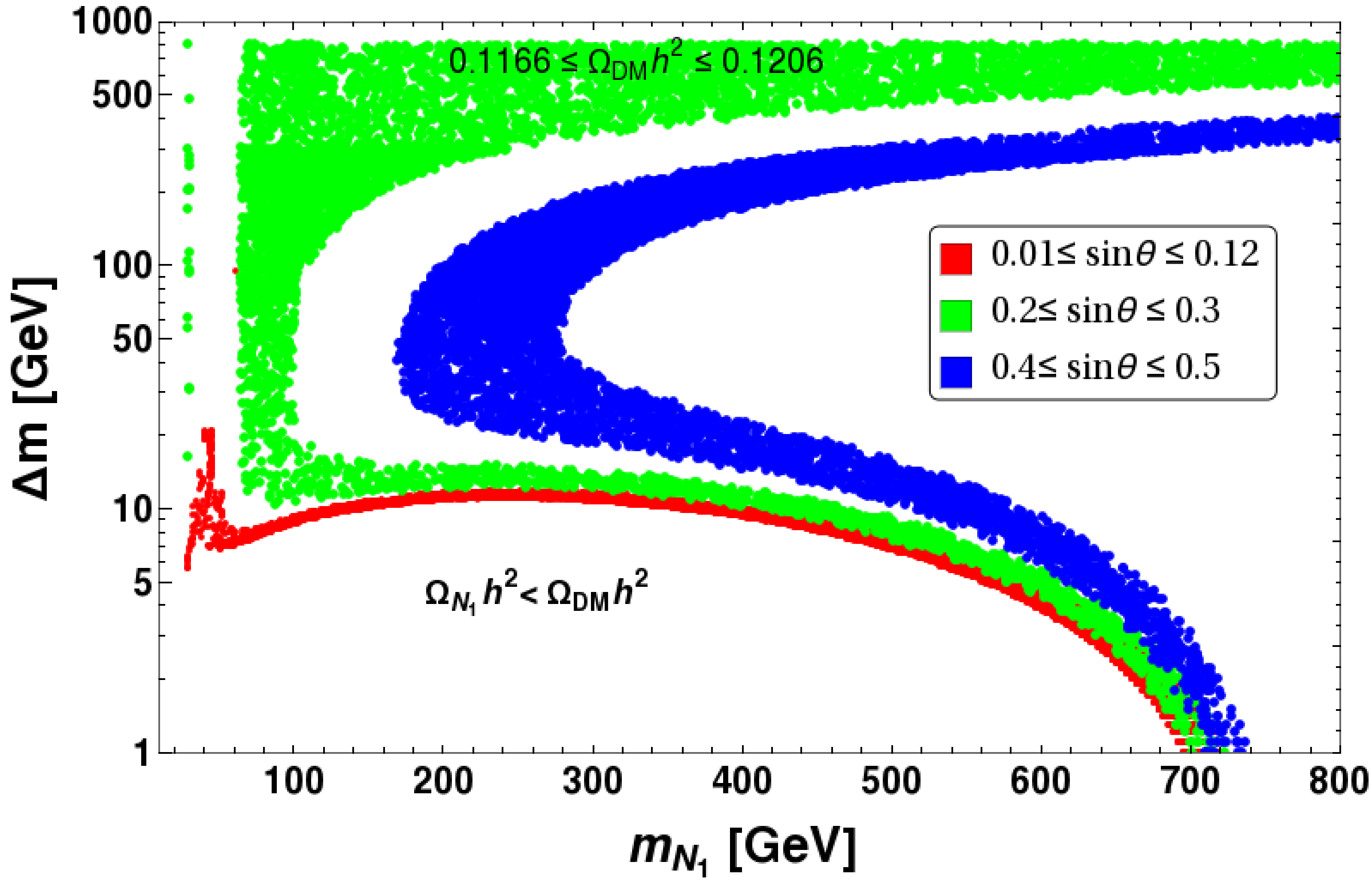


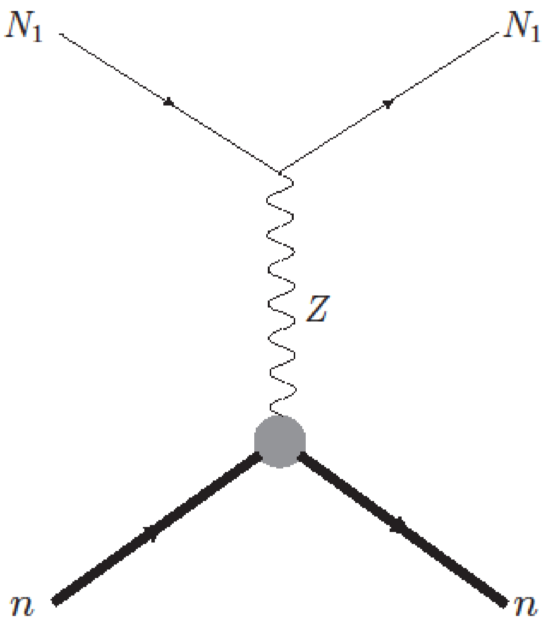
1 ≤ Δm ≤ 10 GeV
0.01 ≤ sinθ ≤ 0.04
0.04 < sinθ ≤ 0.08
0.08 < sinθ ≤ 0.12
$\Omega_{N_1} h^2$
m_{N_1} [GeV]

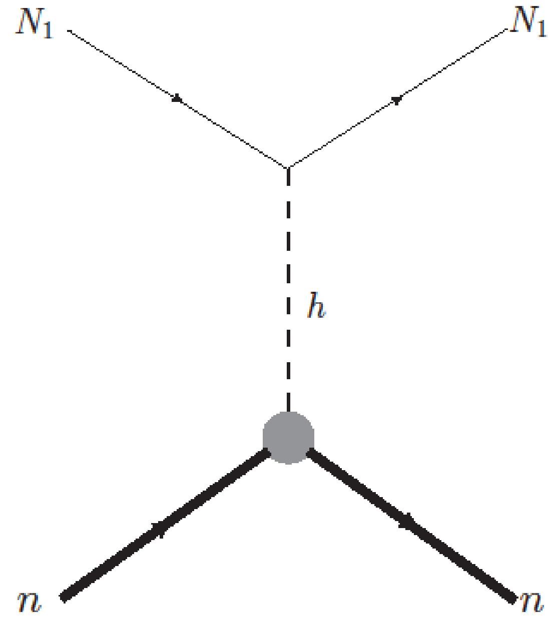


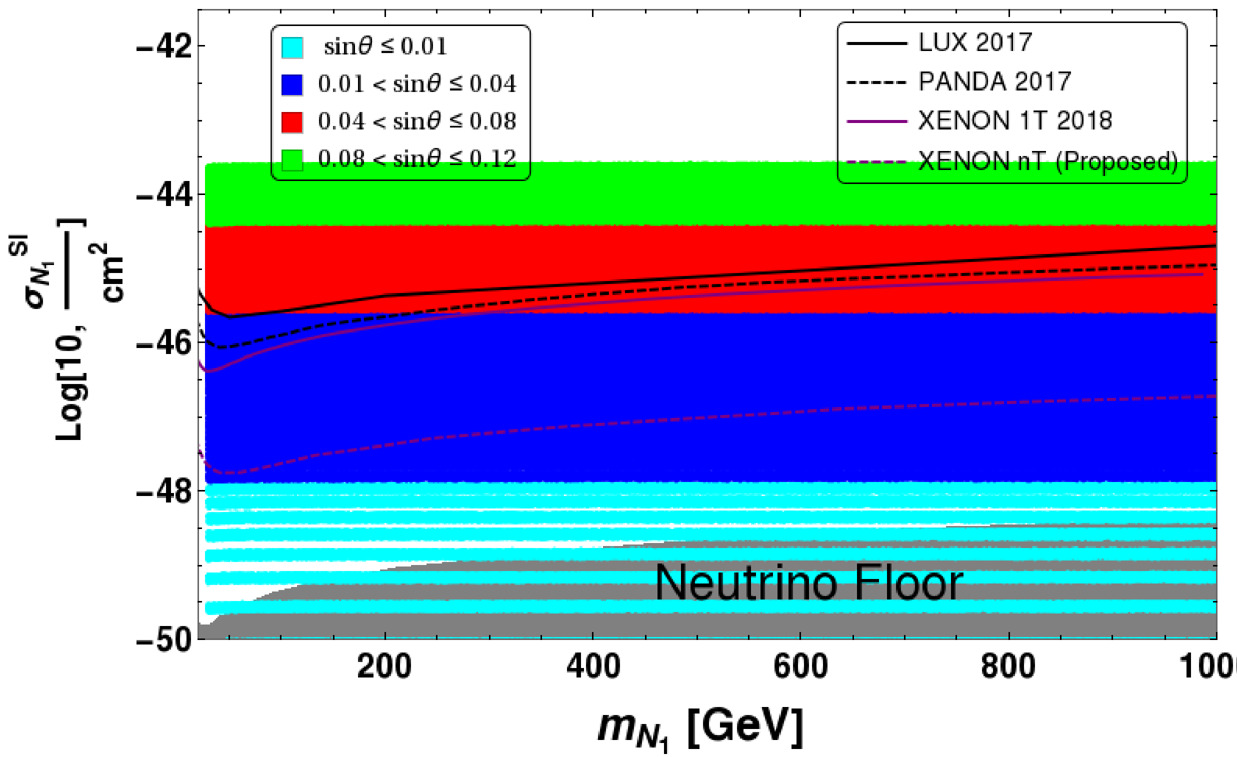
50 ≤ Δm ≤ 100 GeV
0.01 ≤ sinθ ≤ 0.04
0.04 < sinθ ≤ 0.08
0.08 < sinθ ≤ 0.12
$\Omega_{N_1} h^2$
m_{N_1} [GeV]

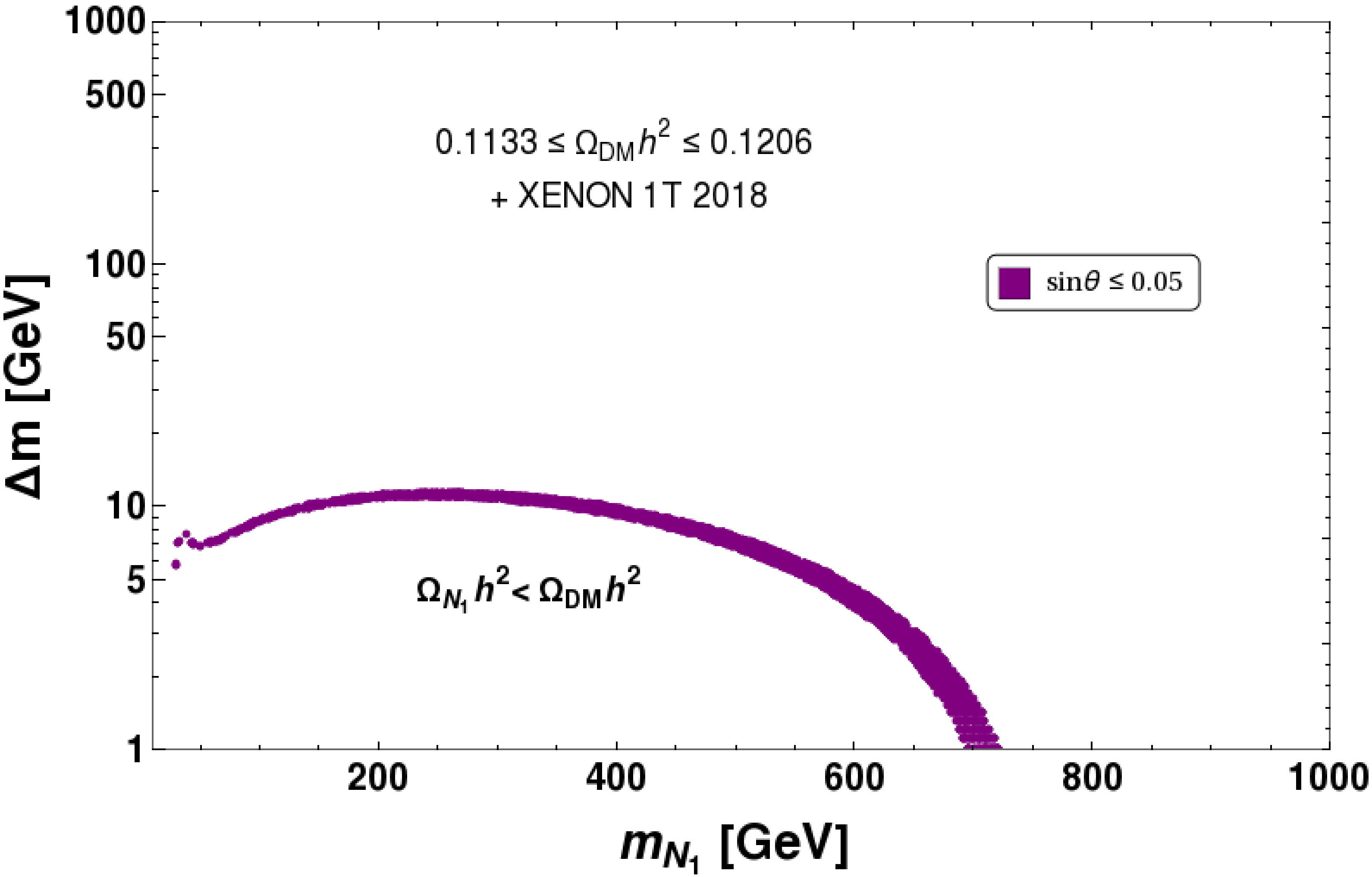
$$Y = \frac{\Delta M \sin 2\theta}{2v}$$




N_1
N_1
Z
n
n


N_1
N_1
h
n
n


sin$\theta \leq 0.01$
$0.01 < \sin\theta \leq 0.04$
$0.04 < \sin\theta \leq 0.08$
$0.08 < \sin\theta \leq 0.12$
LUX 2017
PANDA 2017
XENON 1T 2018
XENON nT (Proposed)
Neutrino Floor
-42
-44
-46
-48
-50
200
400
600
800
1000
Log[10, $\frac{\sigma_{N_1}^{SI}}{cm^2}$]
m_{N_1} [GeV]



1000
500
100
50
10
5
1
0.1133 ≤ $\Omega_{DM}h^2$ ≤ 0.1206
+ XENON 1T 2018
sinθ ≤ 0.05
$\Omega_{N_1}h^2 < \Omega_{DM}h^2$
Δm [GeV]
200
400
600
800
1000
m_{N_1} [GeV]

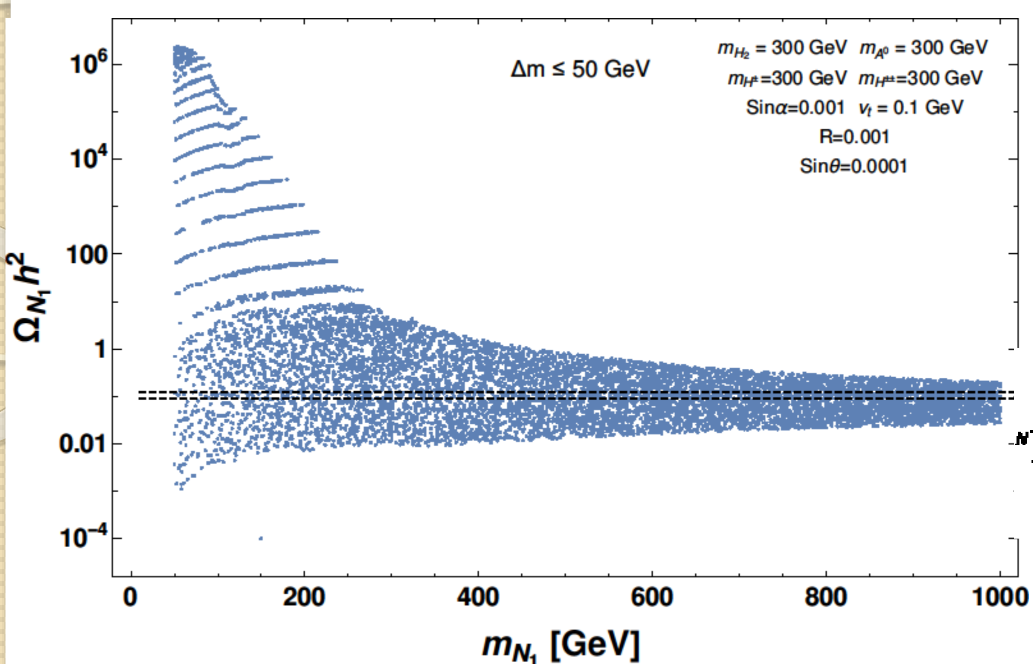
Small singlet-doublet mixing

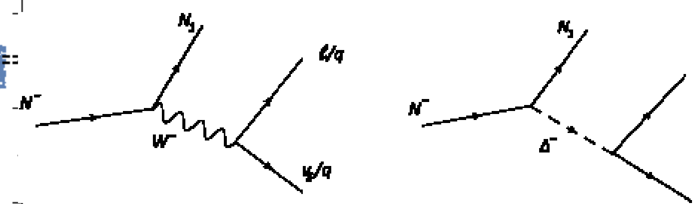
↓

Testing the Hypothesis at collider via displaced vertex signature…

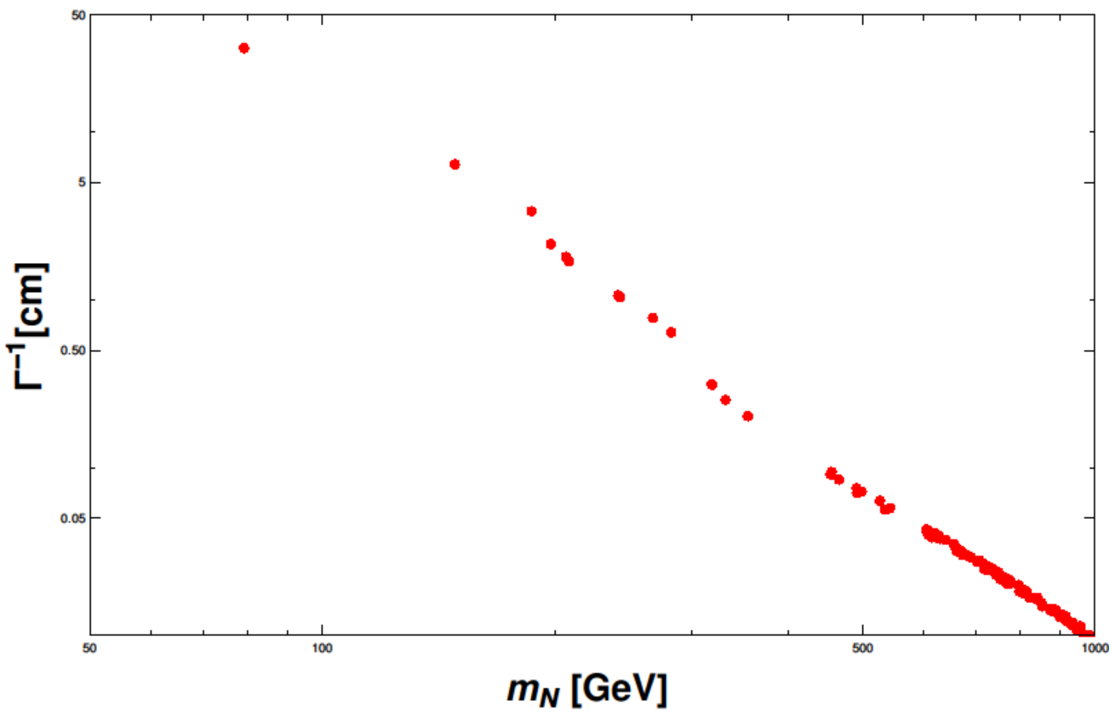
Displaced vertex signature of for small mixing angle:

$$N^{\pm} \rightarrow N_1 + \ell^{\pm} + \nu_{\ell}$$





Thus for a small mass difference we expect a large displaced vertex signature of charged partner of the dark matter.



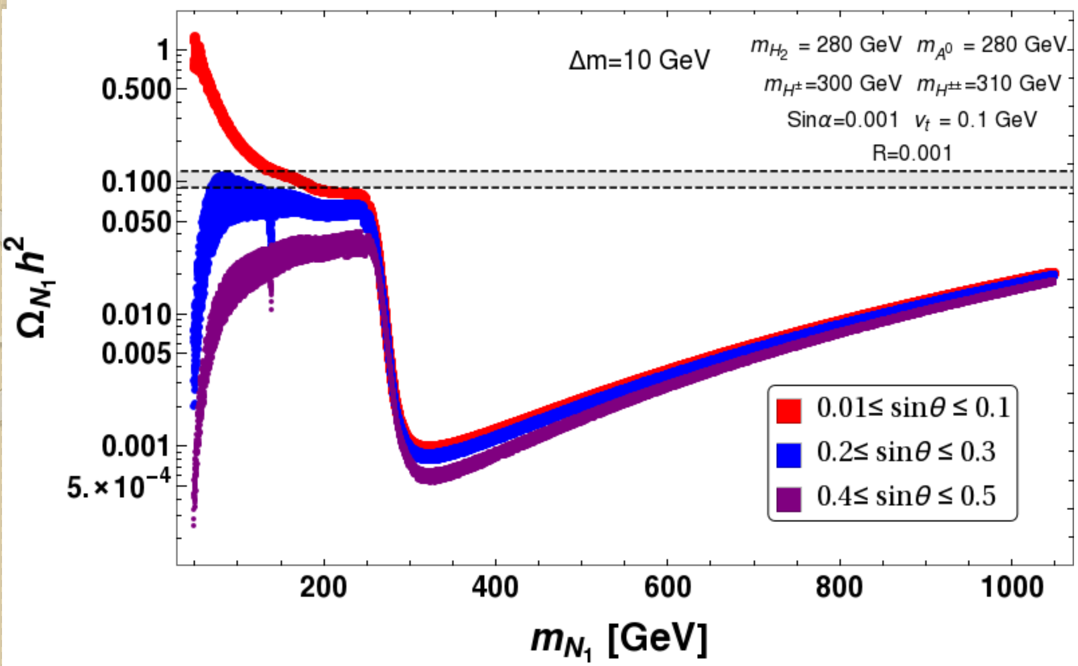
Effect of scalar triplet on Singlet-Doublet fermion DM

(1) The scalar triplet generate sub-eV masses of active neutrinos.

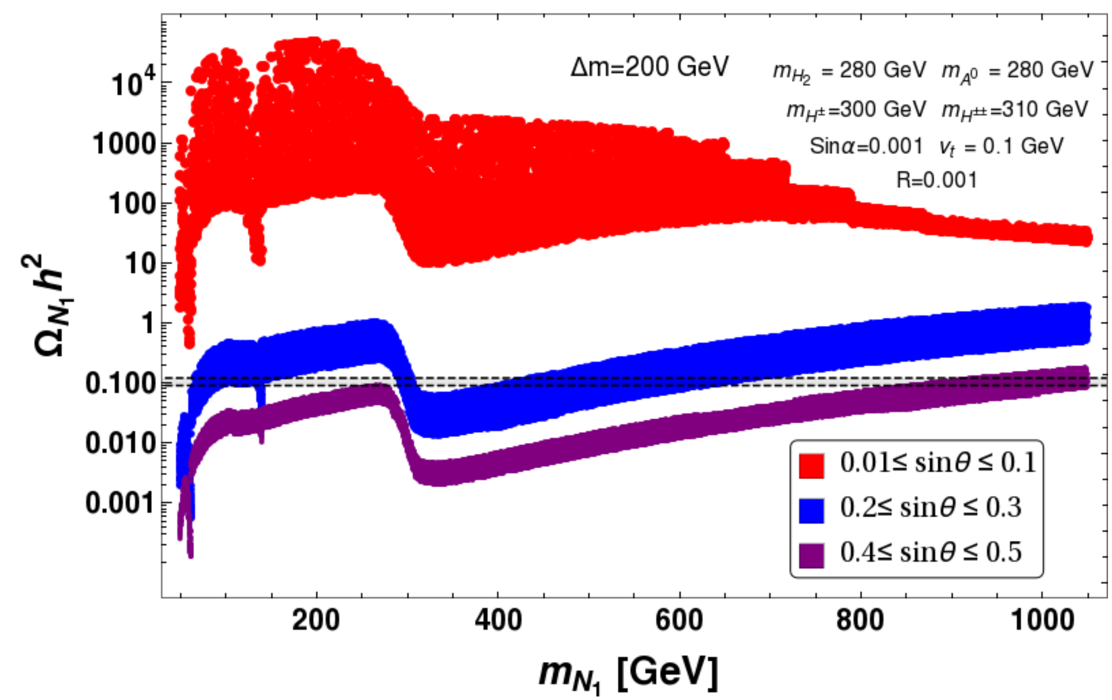
(2) It also splits the singlet-doublet DM in to two pseudo-Dirac states with a mass splitting of order 100 keV, which helps in forbidding the Z-mediated direct detection process.

$$\delta m = 2\sqrt{2} f_N \sin\theta^2 < \Delta >$$

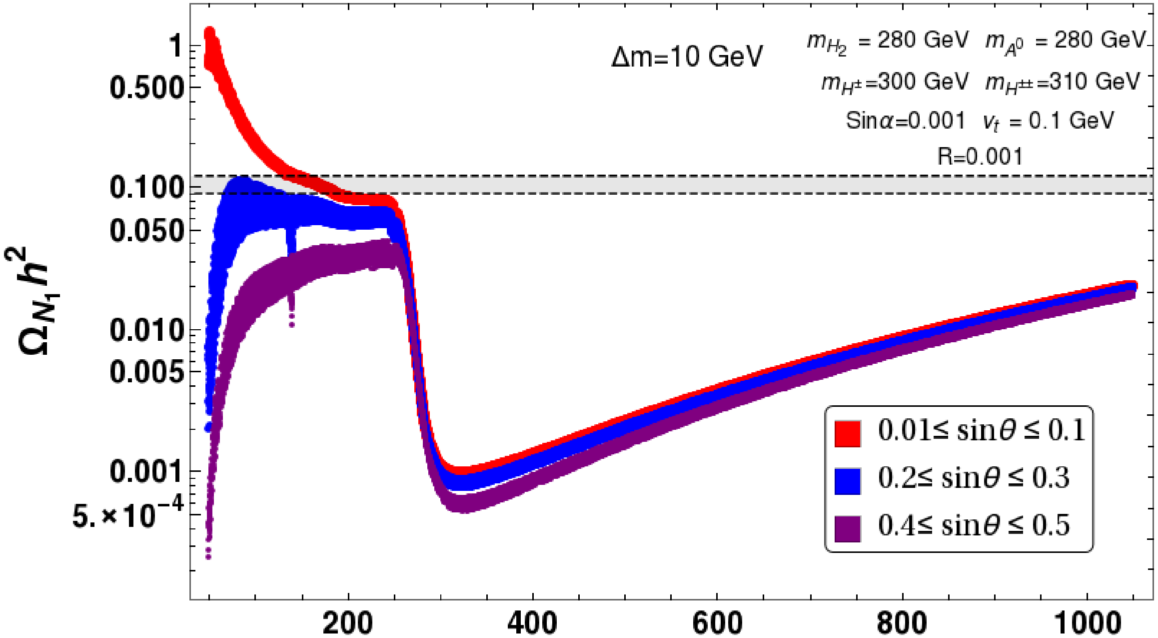
$$R = \frac{M_\nu}{\delta m} < 10^{-3}$$



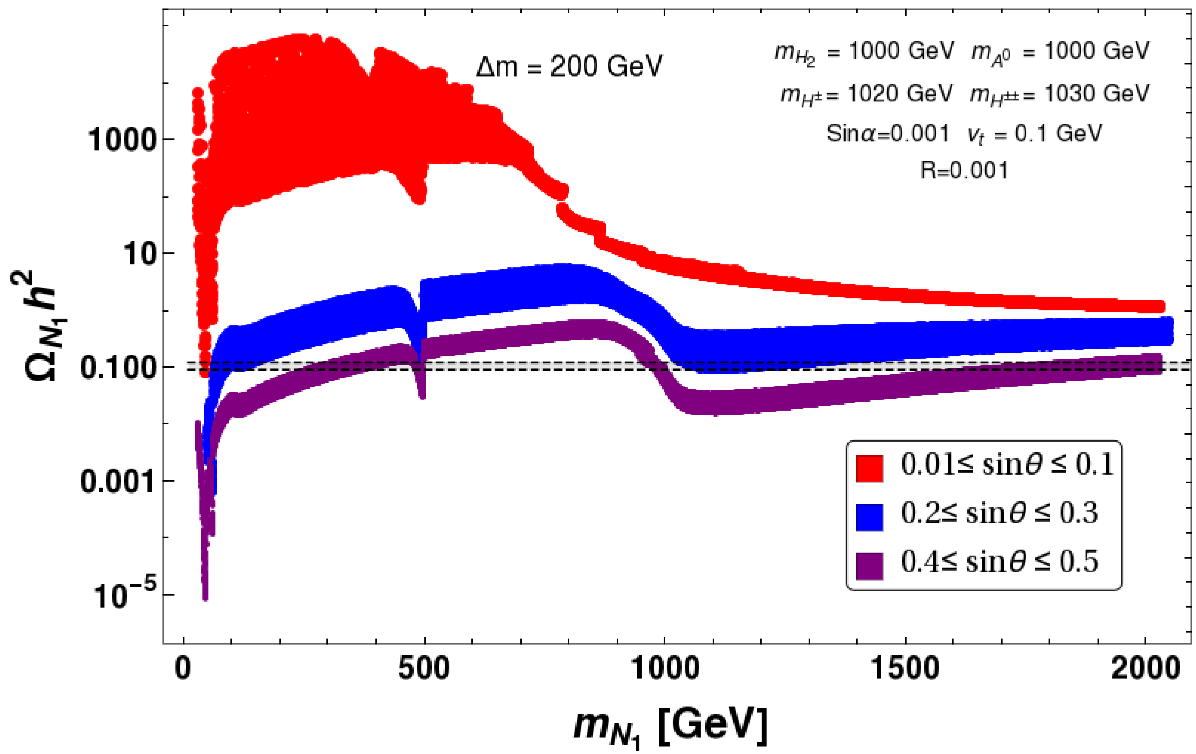
Δm=10 GeV
m_{H_2} = 280 GeV m_{A^0} = 280 GeV
$m_{H^\pm}$=300 GeV $m_{H^{\pm\pm}}$=310 GeV
Sinα=0.001 v_t = 0.1 GeV
R=0.001
0.01≤ sinθ ≤ 0.1
0.2≤ sinθ ≤ 0.3
0.4≤ sinθ ≤ 0.5
$\Omega_{N_1} h^2$
m_{N_1} [GeV]
1
0.500
0.100
0.050
0.010
0.005
0.001
$5.\times10^{-4}$
200
400
600
800
1000



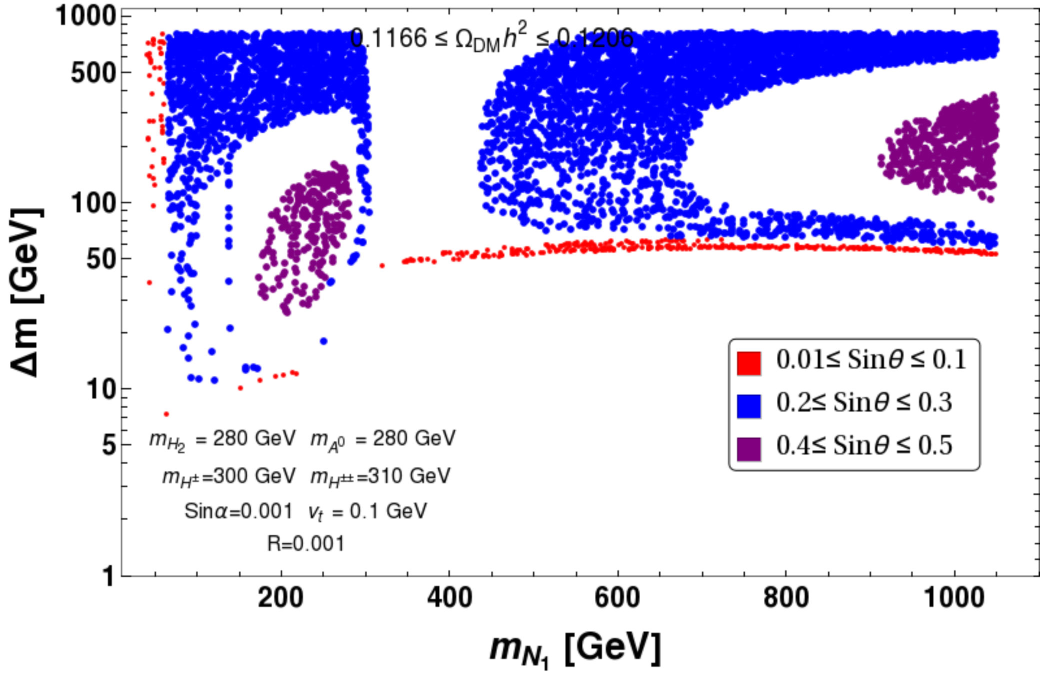
Δm=200 GeV
m_{H_2} = 280 GeV m_{A^0} = 280 GeV
$m_{H^\pm}$=300 GeV $m_{H^{\pm\pm}}$=310 GeV
Sinα=0.001 v_t = 0.1 GeV
R=0.001
0.01≤ sinθ ≤ 0.1
0.2≤ sinθ ≤ 0.3
0.4≤ sinθ ≤ 0.5
$\Omega_{N_1} h^2$
m_{N_1} [GeV]
10^4
1000
100
10
1
0.100
0.010
0.001
200
400
600
800
1000



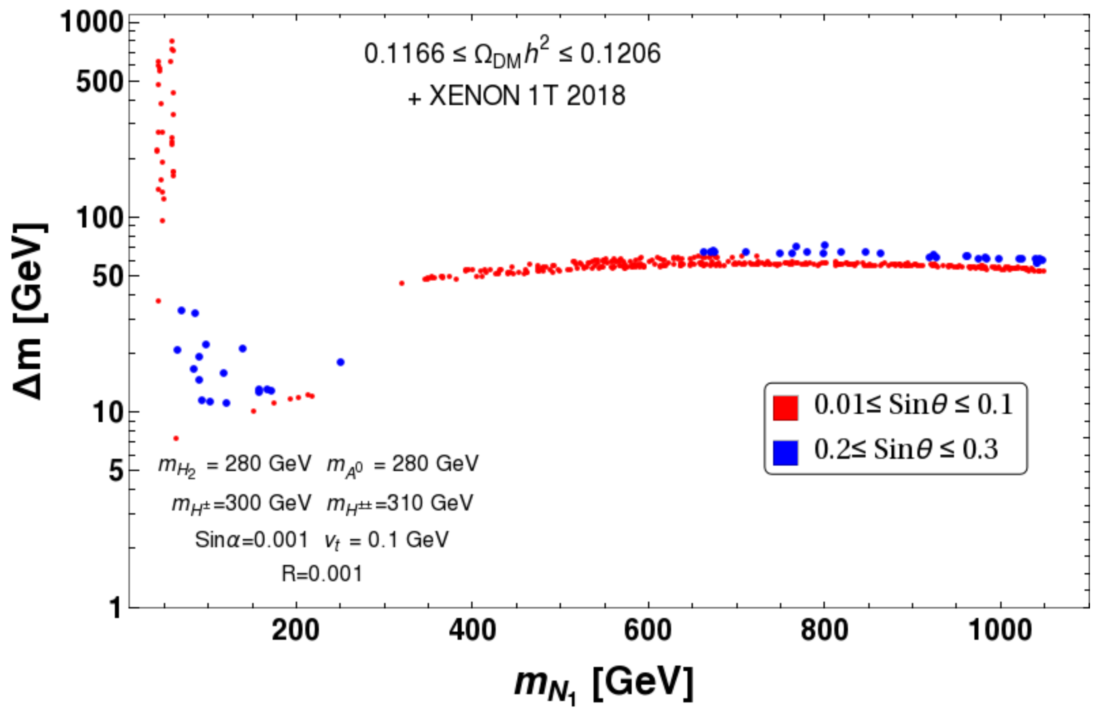
Δm=10 GeV
m_{H_2} = 280 GeV m_{A^0} = 280 GeV
$m_{H^\pm}$=300 GeV $m_{H^{\pm\pm}}$=310 GeV
Sinα=0.001 v_t = 0.1 GeV
R=0.001
$\Omega_{N_1} h^2$
1
0.500
0.100
0.050
0.010
0.005
0.001
$5.\times10^{-4}$
200
400
600
800
1000
0.01≤ sinθ ≤ 0.1
0.2≤ sinθ ≤ 0.3
0.4≤ sinθ ≤ 0.5



Δm = 200 GeV
m_{H_2} = 1000 GeV m_{A^0} = 1000 GeV
$m_{H^\pm}$ = 1020 GeV $m_{H^{\pm\pm}}$ = 1030 GeV
Sinα=0.001 v_t = 0.1 GeV
R=0.001
$\Omega_{N_1} h^2$
1000
10
0.100
0.001
10^{-5}
0
500
1000
1500
2000
m_{N_1} [GeV]
0.01≤ sinθ ≤ 0.1
0.2≤ sinθ ≤ 0.3
0.4≤ sinθ ≤ 0.5



$0.1166 \leq \Omega_{DM} h^2 \leq 0.1206$
$0.01 \leq \mathrm{Sin}\theta \leq 0.1$
$0.2 \leq \mathrm{Sin}\theta \leq 0.3$
$0.4 \leq \mathrm{Sin}\theta \leq 0.5$
m_{H_2} = 280 GeV m_{A^0} = 280 GeV
$m_{H^\pm}$=300 GeV $m_{H^{\pm\pm}}$=310 GeV
Sinα=0.001 v_t = 0.1 GeV
R=0.001
Δm [GeV]
m_{N_1} [GeV]



$0.1166 \leq \Omega_{DM} h^2 \leq 0.1206$
+ XENON 1T 2018
$0.01 \leq \mathrm{Sin}\theta \leq 0.1$
$0.2 \leq \mathrm{Sin}\theta \leq 0.3$
m_{H_2} = 280 GeV m_{A^0} = 280 GeV
$m_{H^\pm}$=300 GeV $m_{H^{\pm\pm}}$=310 GeV
Sinα=0.001 v_t = 0.1 GeV
R=0.001
Δm [GeV]
m_{N_1} [GeV]

Conclusions

(1) The observed relic abundance of DM implies that its freeze-out cross-section (~0.1pb) is typically a weak interaction cross-section. So it is largely believed that the DM is a WIMP.

(2) We studied the case of a mixed (singlet+doublet) leptonic DM which satisfies the relic abundance in a large parameter space.

(3) The spin independent direct detection cross-section is within the reach of Xenon-1T.

(4) The displaced vertex signature of the charged partner of DM looks promising.

(5) In presence of a scalar triplet large singlet-doublet mixing is allowed and hence lead to new collider signatures.

Thank you