Dark Matter Phenomenology in Triplet Extensions of the Standard Model

MS Thesis Mid-Semester Presentation

Niharika Shrivastava (21187)
Supervisor : Dr. Rahul Srivastava

Department of Physics
Indian Institute of Science Education and Research, Bhopal

13th November, 2025

Standard Model of Particle Physics

- Theory that classifies all known elementary particles and describes three of the four fundamental forces: the strong, weak, and electromagnetic forces.

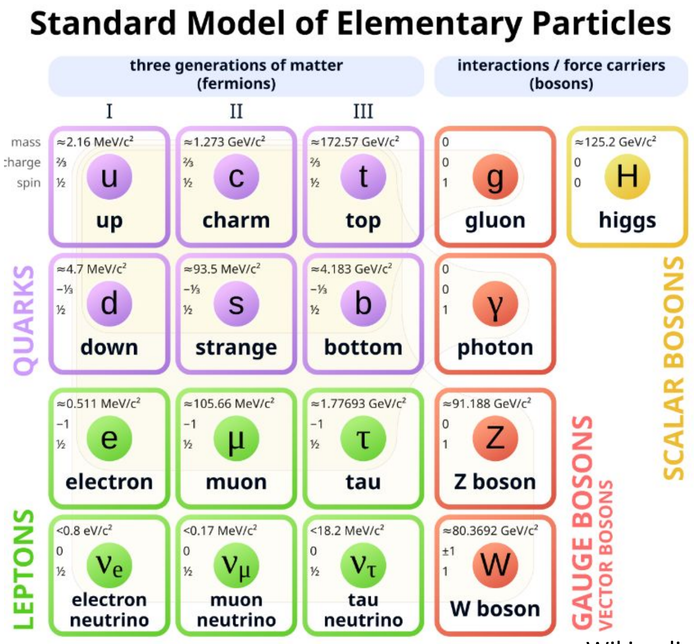
- Gauge (Local) Symmetry Group :

$$G_{SM} = \underbrace{\underbrace{SU(3)_C}_{\text{Color}}}_{\text{Strong}} \times \underbrace{\underbrace{SU(2)_L}_{\text{Left}} \times \underbrace{U(1)_Y}_{\text{Hypercharge}}}_{\text{Electroweak}}$$

- The Standard Model(SM) has been verified experimentally with high precision by particle physics experiment.

- Limitations of SM : Dark Matter(DM), Neutrino Masses, Baryon Asymmetry, Unification with Gravity, Dark Energy

- This makes it evident that SM is not final theory.



Wikipedia

Particle content of SM

Dark Matter

- Form of non-luminous matter which interacts only gravitationally with the visible matter.
- According to current observations, the total energy budget of our universe contains 4.9% ordinary matter, 26.8% DM and 68.3% Dark Energy [2].
- **Evidence for Dark Matter :** Interaction of visible and DM in galaxies shown in galaxy rotation curves, Cosmic Microwave Background(CMB) and Weak gravitational lensing.
- **DM Candidates** : Weakly Interacting Massive Particles (WIMPS), Feebly Interacting Massive Particles (FIMPS), Axions, Ultra-light DM, Sterile Neutrinos, Asymmetric DM, Primordial Black holes etc.

Extension of SM

- To find the particle nature of DM we add new particles to SM with new symmetry to stabilize the DM particle. DM will always be electrically neutral in our theory.
- We add triplet scalar and triplet fermion and perform various tests to find out how DM integrates to SM.

[2] Planck Collaboration 2018

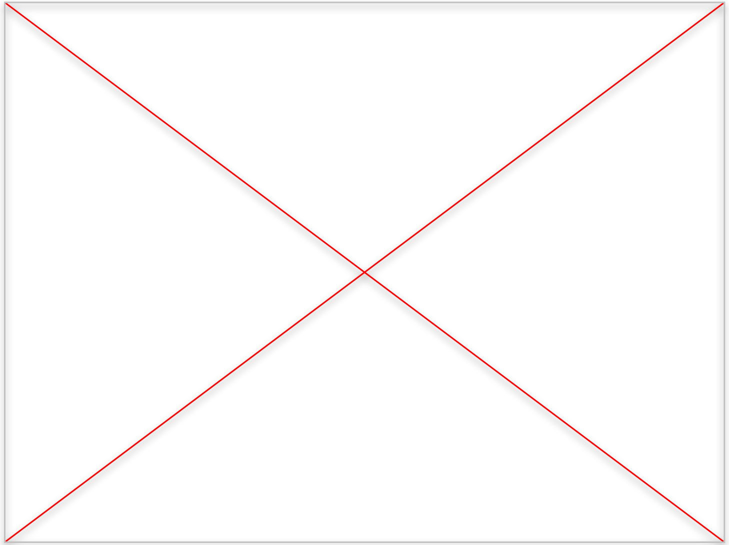
Weakly Interacting Massive Particles (WIMPS)

- Hypothetical particles with masses typically in the GeV–TeV range that interact via the weak nuclear force.

- They naturally achieve the observed relic abundance through the thermal “freeze-out” mechanism, making them one of the most studied dark matter candidates.

- In early Universe, the WIMPS interacted weakly with normal matter then as the universe expanded and cooled, these interactions became too slow, and WIMPs “froze out,” leaving a constant number of them behind which the the DM relic abundance we see today. To a good approximation it is given as [3] :

$$\Omega_{\mathrm{DM}} h^2 \equiv \frac{\rho_{\mathrm{DM}}}{\rho_c/h^2} \simeq 0.119 \, \frac{3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$



NASA

Where $\rho_c = 3(H_0)^2/8\pi G$ is critical density of Universe and h is the hubble rate.

- This means the relic abundance mainly depends on the thermally averaged annihilation cross section $<\sigma v>$.

[3] G.Steigman, B.Dasgupta, JF Beacon, PR2012

Weakly Interacting Massive Particles (WIMPS)

Search for WIMPS

Relic Density

According to current cosmological data, the relic density is[2]

$\Omega h^2 = 0.120 \pm 0.001$

Direct Detection

Measure the recoil from WIMP–nucleon scattering

Experiments : XENONnT[7], LZ[5], and PandaX[6]

Indirect Detection

Search for the secondary particles (like gamma rays, neutrinos) produced when DM particles annihilate in space. Fermi-LAT, H.E.S.S., and CTA.

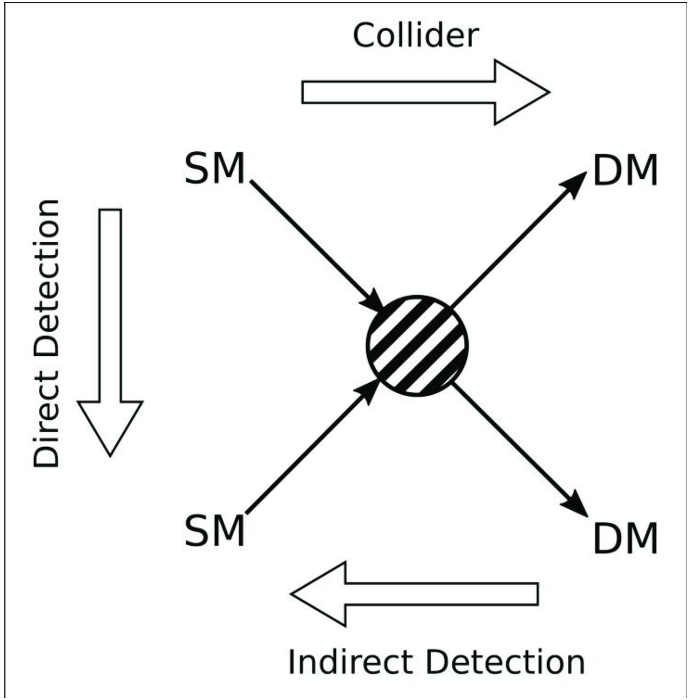
Collider Searches

Produce dark matter particles in high-energy collisions and detect them through missing energy signatures.

ATLAS and CMS at LHC

[2] Planck Collaboration 2018

Search for Dark Matter



Different interactions of DM with SM particles

Model Setup : Basic Formulations

SM Lagrangian

$$\mathcal{L}_{SM} = \underbrace{-\frac{1}{4}G^a_{\mu\nu}G^{a\,\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W^{i\,\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}}_{\text{Gauge sector}} + \underbrace{\sum_\psi \bar{\psi}i\gamma^\mu D_\mu\psi}_{\text{Fermion sector}} + \underbrace{(D_\mu\Phi)^\dagger(D^\mu\Phi) - V(\Phi)}_{\text{Higgs sector}} - \underbrace{\mathcal{L}_{\text{Yukawa}}}_{\text{Yukawa interactions}}$$

- Each piece ensures the SM remains **Lorentz invariant**, **renormalizable**, and **gauge invariant** under the symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$.

- Charge of each particle is given by :

$$Q = T_3 + Y/2$$

T_3 = Charge under third $SU(2)_L$ generator
Y = hypercharge under $U(1)_Y$

Gauge Group	Baryon Fields			Lepton Fields		Scalar Field
	$Q^i_L = (u^i_L, d^i_L)^T$	u^i_R	d^i_R	$L^i_L = (\nu^i_L, e^i_L)^T$	e^i_R	H
$SU(3)_c$	3	3	3	1	1	1
$SU(2)_L$	2	1	1	2	1	2
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	1/2
$\mathbb{Z}_2$	+	+	+	+	+	+

Model Setup : Scalar Triplet

$$\mathscr{L}_{\text{scalar}} = \underbrace{(D_\mu H)^\dagger (D^\mu H) + \mathrm{Tr}\left[(D_\mu \Delta_2)^\dagger (D^\mu \Delta_2)\right]}_{\text{Kinetic terms}}$$

$$\underbrace{- \Big(-\mu^2 H^\dagger H + \mu_{\Delta_2}^2 \mathrm{Tr}[\Delta_2^\dagger \Delta_2] + \tfrac{1}{2}\lambda_H (H^\dagger H)^2 + \tfrac{1}{2}\lambda_\Delta \mathrm{Tr}[\Delta_2^\dagger \Delta_2 \Delta_2^\dagger \Delta_2] + \tfrac{1}{2}\lambda'_\Delta \left(\mathrm{Tr}[\Delta_2^\dagger \Delta_2]\right)^2 + \tfrac{1}{2}\lambda_{H\Delta} H^\dagger H \,\mathrm{Tr}[\Delta_2^\dagger \Delta_2] + \tfrac{1}{2}\lambda'_{H\Delta} H^\dagger (\Delta_2 \Delta_2^\dagger) H \Big)}_{\text{Mass and Interaction terms}}$$

Gauge Group	Triplet Δ_2
$SU(3)_c$	1
$SU(2)_L$	3
$U(1)_Y$	2
$\mathbb{Z}_2$	$-$

$$\Delta_2 = \begin{pmatrix} \Delta_1^2 \\ \Delta_2^2 \\ \Delta_3^2 \end{pmatrix}$$

Hence, in adjoint representation our triplet becomes,

$$\Delta_2 = \begin{pmatrix} \frac{\Delta_2^+}{\sqrt{2}} & \Delta_2^{++} \\ \Delta_2^0 & -\frac{\Delta_2^+}{\sqrt{2}} \end{pmatrix}$$

where $\Delta_2^0 = \Delta_{2R}^0 + i\Delta_{2I}^0$, and Δ_2^+, Δ_2^{++}. Δ_{2R}^0 is our DM candidate.

Model Setup : Fermionic Triplet

$$\mathscr{L}_{\Sigma_2} = \underbrace{\mathrm{Tr}\left[\overline{\Sigma_2}\, i\gamma^\mu D_\mu \Sigma_2\right]}_{\text{Kinetic term}} \underbrace{- M\,\mathrm{Tr}(\overline{\Sigma}_{2L}\Sigma_{2R}) + \mathrm{h.c.}}_{\text{Dirac mass term}}$$

$$\Sigma_{2L} = \frac{1}{2}\begin{pmatrix} \Sigma_2^+ & \sqrt{2}\Sigma_2^{++} \\ \sqrt{2}\Sigma_2^0 & -\Sigma_2^+ \end{pmatrix} \quad , \quad \Sigma_{2R} = \frac{1}{2}\begin{pmatrix} \Sigma_2^+ & \sqrt{2}\Sigma_2^{++} \\ \sqrt{2}\Sigma_2^0 & -\Sigma_2^+ \end{pmatrix}$$

The mass for all three particles will be the same at tree level, and the differences will occur due to one-loop mass corrections such that the neutral component Σ_2^0 will be the lightest, making it the dark matter candidate.

Gauge Group	**Triplet** Σ_2
$SU(3)_c$	1
$SU(2)_L$	3
$U(1)_Y$	2
$\mathbb{Z}_2$	$-$

DM Phenomenology

- Phenomenology focuses on exploring the particle nature, production mechanisms, and observational signatures of DM beyond the SM.

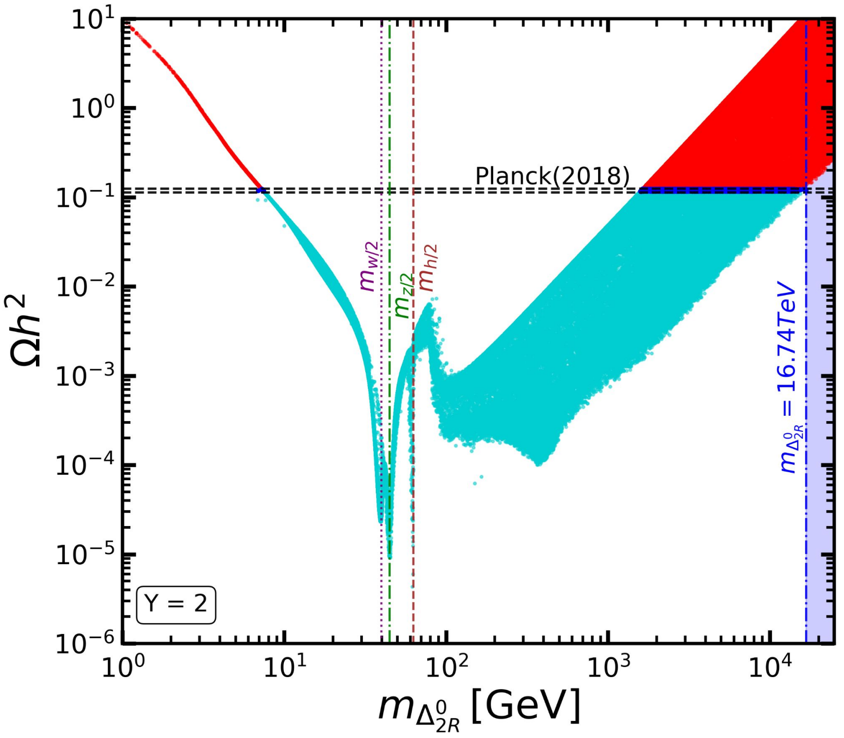
- For the implementation of triplet models, we use `SARAH`. Then use, `SPheno` to calculate decays and physical particle mass spectrum with the files generated by `SARAH` as input.

- Dark matter relic abundance, and dark matter-nucleon cross section at tree level are calculated with `MicrOmegas`.

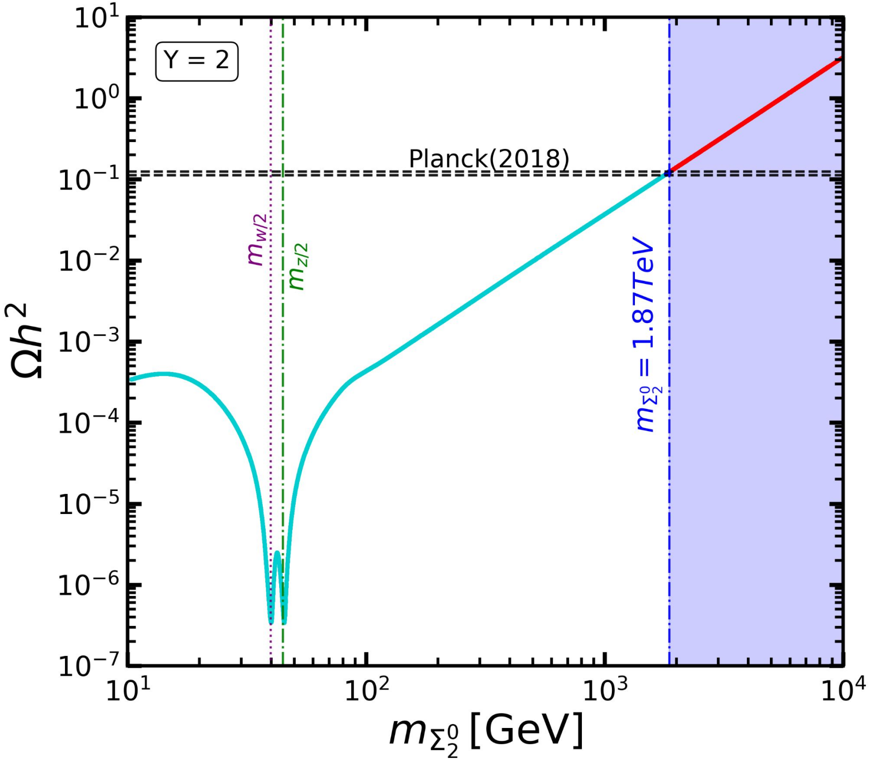
- We investigate the phenomenological viability of the triplet scalar and triplet DM model by performing a systematic scan over the relevant parameter space of model.

- Parameters for Scalar Triplet : $\boldsymbol{\lambda}_H$, $\boldsymbol{\lambda}_{\boldsymbol{\Delta}}$, $\boldsymbol{\lambda}'_{\boldsymbol{\Delta}}$, $\boldsymbol{\lambda}_{H\boldsymbol{\Delta}}$, $\boldsymbol{\lambda}'_{H\boldsymbol{\Delta}}$, $\mu_{\boldsymbol{\Delta}}^2$
  Fermionic Triplet : $\boldsymbol{\lambda}_H$, M

Results : Relic Density Plots

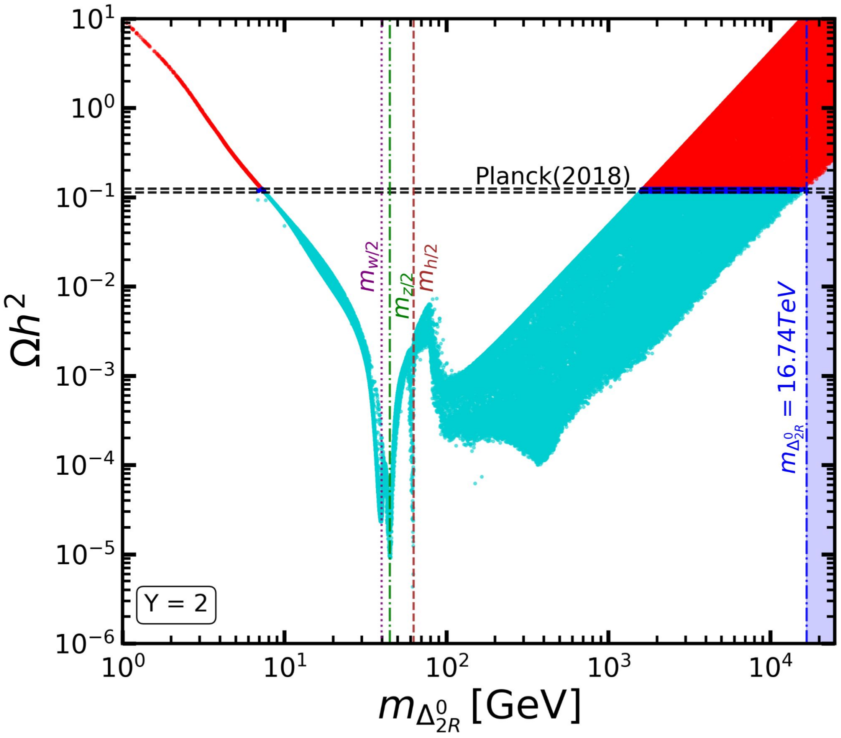


Scalar Triplet

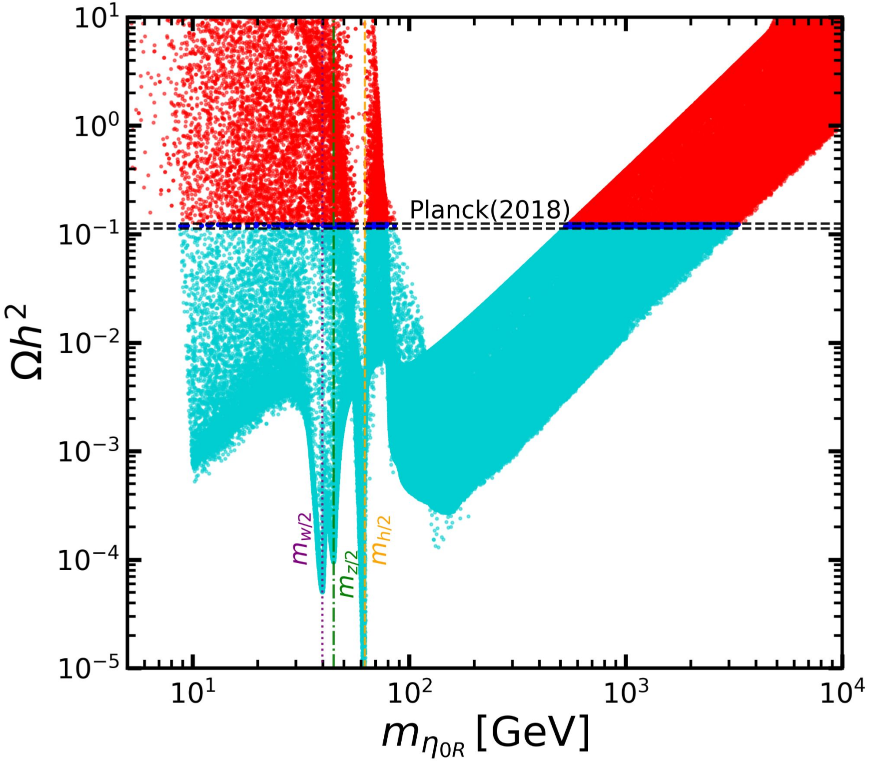


Fermionic Triplet

Motivation for Triplet Case

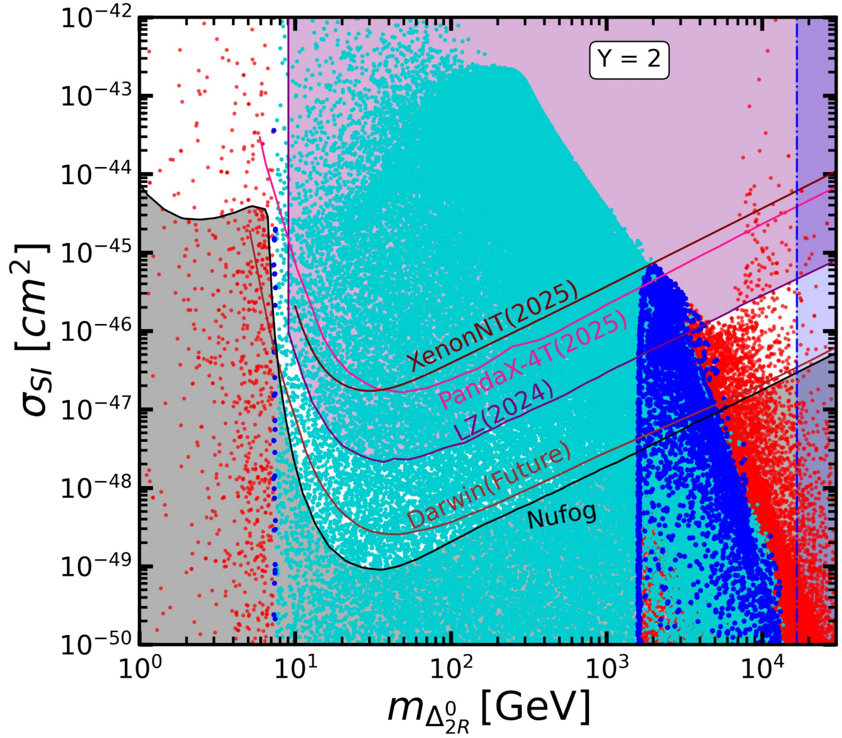


Scalar Triplet

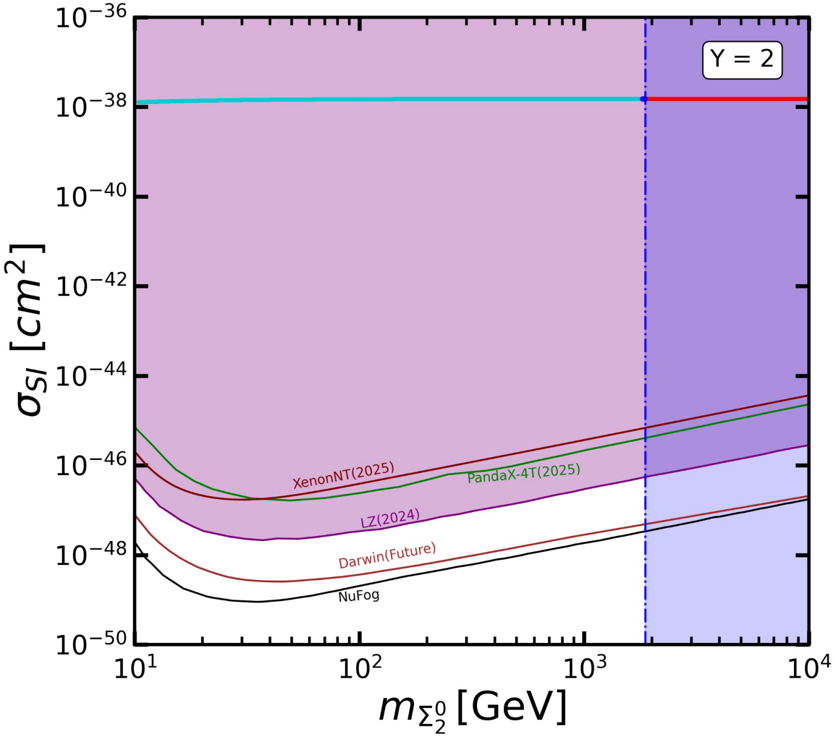


Scotogenic Model [4]

Results : Direct Detection



Scalar Triplet



Fermionic Triplet

Discussion & Future Work

Mass of DM range	Scalar Triplet	Fermionic triplet
Relic Abundance	1.59 - 16.74 TeV	1.81 - 1.87 TeV
Direct Detection	1.59 - 5.70 TeV	x

- Scalar triplet model survived both relic abundance and direct detection limits for narrow mass range whereas no points satisfy direct detection limits for the fermionic case.
- Comparison with doublet case as scotogenic we understand triplet has narrow range of relic satisfying mass region hence easier to probe.
- We plan to perform an indirect detection analysis for both models by plotting the annihilation cross section.
- In addition, we aim to carry out a detailed collider phenomenology study, wherein we will analyze the relevant decay processes and compute the corresponding production cross sections.

References

1. Planck Collaboration, “Planck 2018 results. vi. cosmological parameters,” Astronomy Astrophysics 641 (2020) A6, arXiv:1807.06209.
2. G. Steigman, B. Dasgupta, and J. F. Beacom, “Precise relic wimp abundance and its impact on searches for dark matter annihilation,” Physical Review D 86 no. 2, (July, 2012) . http://dx.doi.org/10.1103/PhysRevD.86.023506.
3. Ernest Ma. Verifiable radiative seesaw mechanism of neutrino mass and dark matter. Physical Review D, 73(7), April 2006. ISSN 1550-2368. doi:10.1103/physrevd.73.077301. URL http://dx.doi.org/10.1103/PhysRevD.73.077301.
4. LZ Collaboration, J. Aalbers et al., “Dark Matter Search Results from 4.2 Tonne-Years of Exposure of the LUX-ZEPLIN (LZ) Experiment,” Phys. Rev. Lett. 135 no. 1, (2025) 011802, arXiv:2410.17036 [hep-ex].
5. PandaX Collaboration, Z. Bo et al., “Dark Matter Search Results from 1.54 Tonne·Year Exposure of PandaX-4T,” Phys. Rev. Lett. 134 no. 1, (2025) 011805, arXiv:2408.00664 [hep-ex].
6. XENON Collaboration, E. Aprile et al., “WIMP Dark Matter Search using a 3.1 tonne × year Exposure of the XENONnT Experiment,” arXiv:2502.18005 [hep-ex].

Thank you for being a patient listener.

Questions??

Scalar Triplet : Vacuum Stability Conditions

Vacuum Stability Conditions for Y=2 Scalar Triplet

$$\lambda_H > 0,\, \lambda_\Delta + \lambda'_\Delta > 0,\, \lambda'_\Delta + \frac{\lambda_\Delta}{2} > 0$$

$$\lambda_{H\Delta} + \sqrt{2\lambda_H(\lambda_\Delta + \lambda'_\Delta)} > 0,\, \lambda_{H\Delta} + \sqrt{2\lambda_H\left(\lambda'_\Delta + \frac{\lambda_\Delta}{2}\right)} > 0,$$

$$\lambda_{H\Delta} + \lambda'_{H\Delta} + \sqrt{2\lambda_H(\lambda_\Delta + \lambda'_\Delta)} > 0,\, \lambda_{H\Delta} + \lambda'_{H\Delta} + \sqrt{2\lambda_H\left(\lambda'_\Delta + \frac{\lambda_\Delta}{2}\right)} > 0. \tag{8}$$

Scalar Triplet : Masses of Triplet Particles

Mass for Triplet Scalar

$$m_h^2 = \lambda_H v^2,$$

$$m^2_{\Delta_R^0} = m^2_{\Delta_I^0} = M^2 + \frac{1}{4}(\lambda_{H\Delta} + \lambda'_{H\Delta})v^2,$$

$$m^2_{\Delta_2^\pm} = M^2 + \frac{1}{4}\left(\lambda_{H\Delta} + \frac{\lambda'_{H\Delta}}{2}\right)v^2 = m^2_{\Delta^0_{2R}\,(\Delta^0_{2I})} - \frac{\lambda'_{H\Delta}}{8}v^2,$$

$$m^2_{\Delta_2^{\pm\pm}} = M^2 + \frac{1}{4}\lambda_{H\Delta}v^2 = m^2_{\Delta^0_{2R}\,(\Delta^0_{2I})} - \frac{\lambda'_{H\Delta}}{4}v^2.$$

v is the vacuum expectation value of Higgs. (9)

Parameter Ranges

Parameter	Range
λ_H	0.2555
$\mu^2_{\Sigma_2}$	$[10^2, 10^8]$ GeV^2

(a) Fermion triplet

Parameter	Range
λ_H	0.2555
λ_Δ	$\pm[10^{-8}, 4\pi]$
λ'_Δ	$\pm[10^{-8}, 4\pi]$
$\lambda_{H\Delta}$	$\pm[10^{-8}, 4\pi]$
$\lambda'_{H\Delta}$	$\pm[10^{-8}, 4\pi]$
$\mu^2_{\Delta_2}$	$[10^2, 10^8]$ GeV^2

(b) Scalar triplet

Table: Parameter space ranges used in the scan for fermion and scalar triplets.

Adjoint Representation

We can write complex triplet in bidoublet form that makes gauge-invariant contraction easy. It can be written in 2×2 matrix representation by expending them in pauli matrices as $\Delta_2 = \frac{1}{\sqrt{2}}\sigma_i \Delta_2^i$, where σ_i are pauli matrices $\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

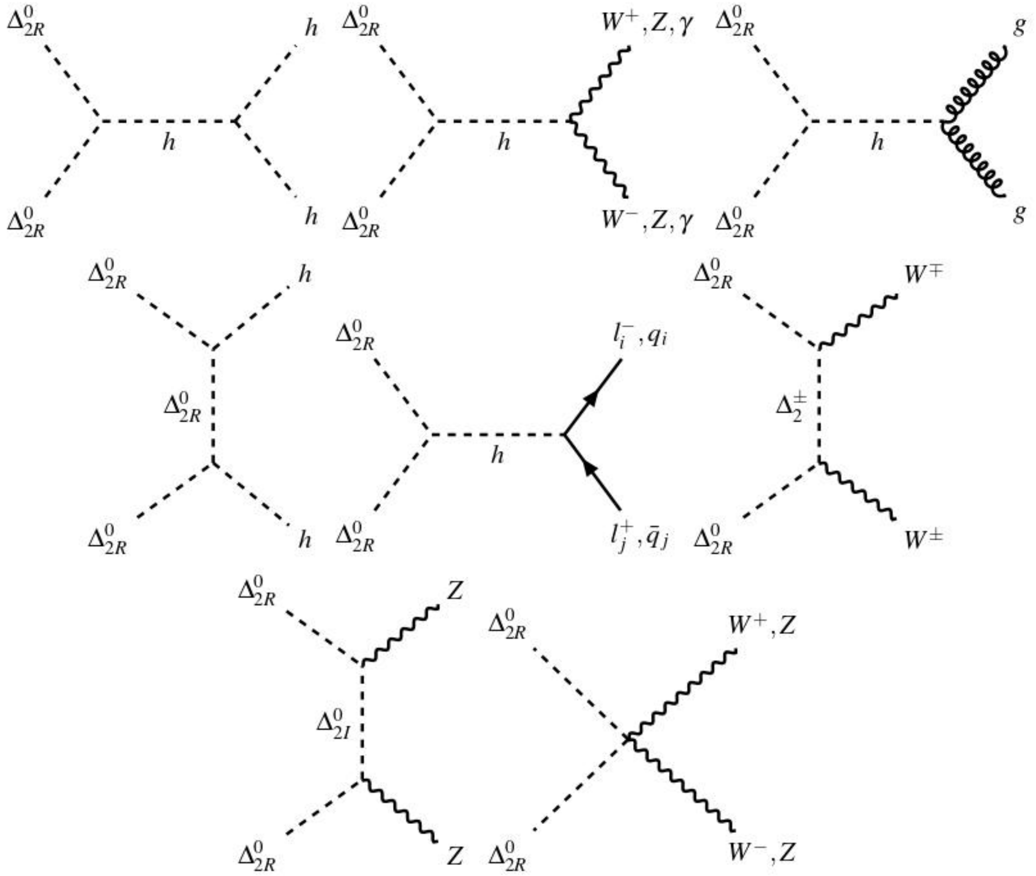
$$\Delta_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \Delta_2^3 & \Delta_2^1 - i\Delta_2^2 \\ \Delta_2^1 + i\Delta_2^2 & -\Delta_2^3 \end{pmatrix} \tag{1}$$

where $\Delta_2^+(Q=+1) \equiv \Delta^3, \quad \Delta^{++}(Q=+2) = \frac{\Delta_2^1 - i\Delta_2^2}{\sqrt{2}}$ and $\quad \Delta_2^0(Q=0) = \frac{\Delta_2^1 + i\Delta_2^2}{\sqrt{2}}$.
Hence, in adjoint representation our triplet becomes,

$$\Delta_2 = \begin{pmatrix} \frac{\Delta_2^+}{\sqrt{2}} & \Delta_2^{++} \\ \Delta_2^0 & -\frac{\Delta_2^+}{\sqrt{2}} \end{pmatrix}$$

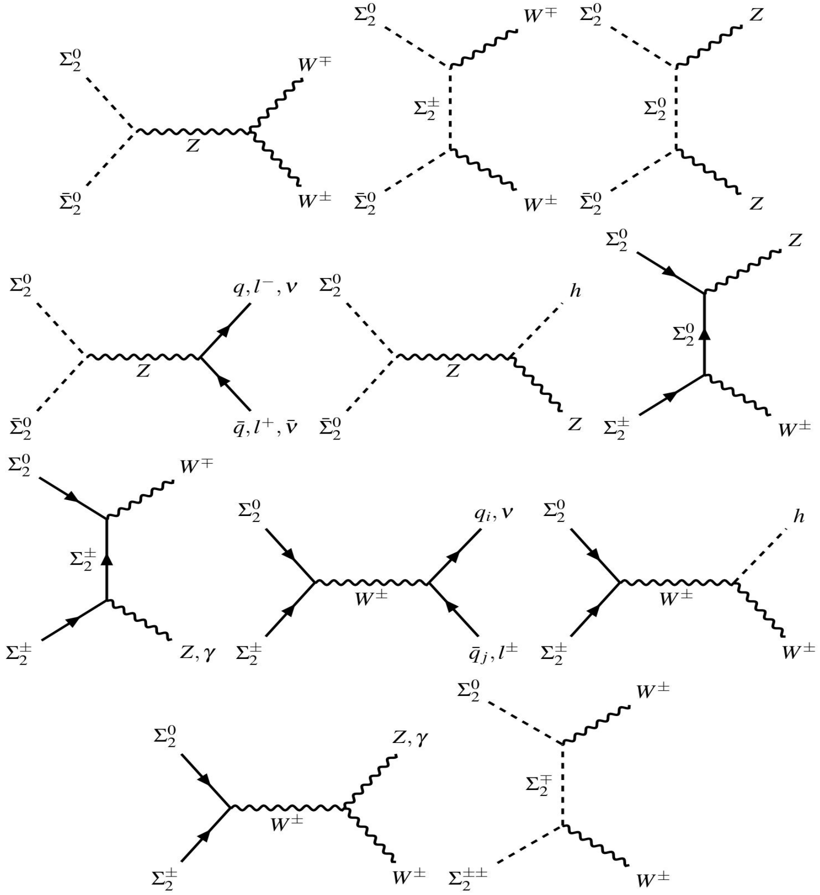
where $\Delta_2^0 = \Delta_{2R}^0 + i\Delta_{2I}^0$, and Δ_2^+, Δ_2^{++}.

Relic Density Annihilation Processes - Scalar triplet



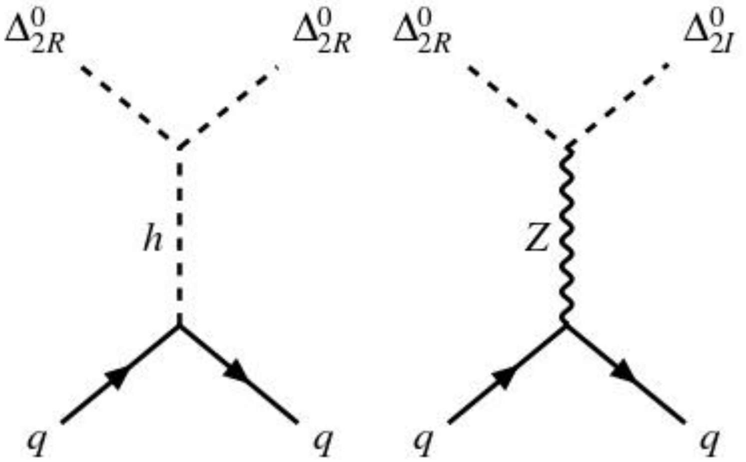
Relevant diagrams for
the direct detection of the scalar
triplet of hypercharge 2.

Relic Density Annihilation Processes - Fermionic Triplet



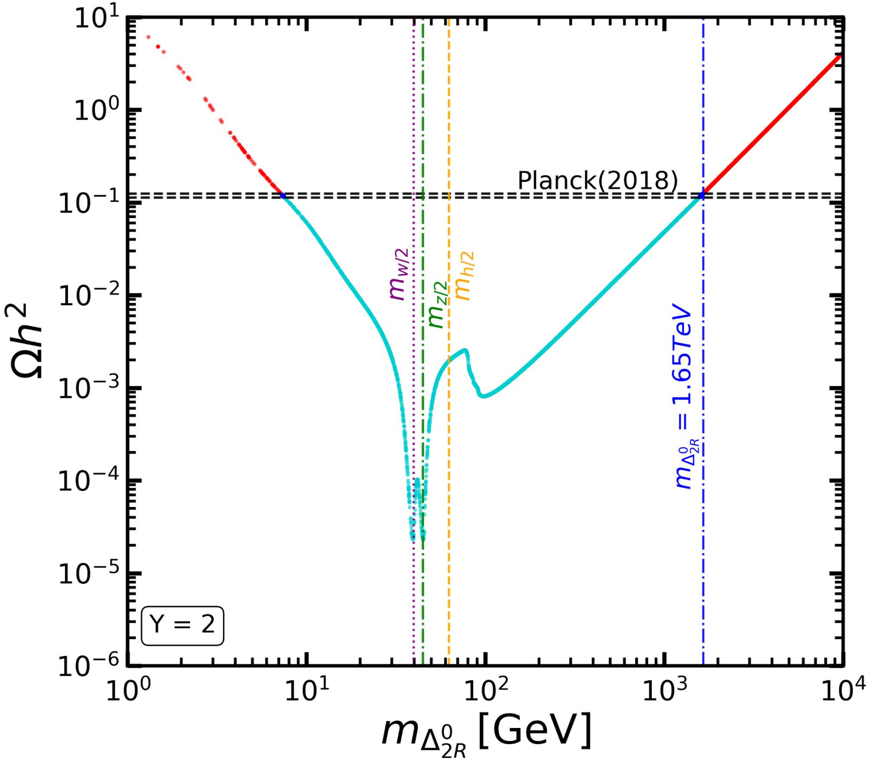
Relevant diagrams (Annihilation and Co-annihilation Channels) for computing the relic density of fermion triplet of hypercharge 2.

Direct Detection - Scalar Triplet



Relevant diagrams for the direct detection of the scalar triplet of hypercharge 2.

Scalar Triplet Relic Density Plot for Zero Higgs Coupling



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- In early Universe, the WIMPS interacted weakly with normal matter then as the universe expanded and cooled, these interactions became too slow, and WIMPs "froze out," leaving a constant number of them behind which the the DM relic abundance we see today. To a good approximation it is given as [3] :

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  Where $\rho_c = 3(H_0)^2 / 8 \pi G$ is critical density of Universe and h is normalised hubble rate.

- This means the relic abundance mainly depends on the thermally averaged annihilation cross section $<\sigma v>$.