Singlet scalar Dark matter in a $U(1)_{B-L}$ model without right-handed neutrinos

Rukmani Mohanta

University of Hyderabad

December 12, 2017

Based on: arXiv:1704.01107 with S. Singirala and S. Patra

SUSY 2017, TIFR Mumbai, India

Dec 11-15, 2017

Outline

1. Brief Introduction
2. Model Description
3. Dark Matter Observables
    - Relic Abundance
    - Collider Limits
    - Semi Annihilation
    - Indirect Searches
4. Light Neutrino mass generation
5. Conclusion

Introduction

- It is widely believed that WIMPS satisfy the necessary criteria of DM, with mass not too far from EW scale
- Thus, provide the opportunity to test them at the current and future direct and indirect DM detection expts.
- To accommodate DM, SM has to be extended with new particle and new symmetry.
- Baryon (B) and Lepton (L) numbers are accidental global symmetries in SM. B must be violated to explain BAU and L will be violated if light ν_i's are Majorana particles
- However, B, L, as well as $(B-L)$ can be local gauge symmetries.
- Models in which $B-L$ is gauged, are economical and well-motivated extensions of SM
- When SM is extended by the local $B-L$ symmetry, anomalies are not automatically cancelled.
- The simple way out is to introduce three right-handed neutrinos

Another variant of $B - L$ Model

- One of the fundamental questions is how to address the stability of DM
- In the conventional $B - L$ gauge models the stability is ensured by imposing the adhoc discrete symmetry on top of gauge symmetry
- In these class of models one of the RH introduced for gauge anomaly cancellation is odd under the discrete symmetry, and acts like potential DM candidate.
- Thus, one of the interesting aspects of $B - L$ models is that, in its standard form, the RH ν's and thus Type-I seesaw mechanism appears naturally.
- Alternatively, one can introduce three exotic fermions with $B - L$ charges as $-4, -4, +5$
- It is easy to check that all potential anomalies are cancelled in this simple framework.
- Due to their special $B - L$ charge new fermions do not couple directly to the SM fermion.

Anomaly cancellation in $B-L$ model

- SM fermion content is insufficient to cancel the triangle gauge anomalies

$$\mathcal{A}^{\rm SM}\left[(\text{gravity})^2\times U(1)_{B-L}\right]=-3,\quad \mathcal{A}^{\rm SM}\left[U(1)^3_{B-L}\right]=-3.$$

- With the introduction of three exotic fermions with $B-L$ charges $-4,-4,+5$

$$\begin{aligned}
\mathcal{A}\left[U(1)^3_{B-L}\right] &= \mathcal{A}_1^{\rm SM}\left(U(1)^3_{B-L}\right)+\mathcal{A}_1^{\rm New}\left(U(1)^3_{B-L}\right)\\
&= -3+(4)^3+(4)^3+(-5)^3=0\,,\\
\mathcal{A}\left[\text{gravity}^2\times U(1)_{B-L}\right] &= \mathcal{A}_1^{\rm SM}\left(U(1)_{B-L}\right)+\mathcal{A}_1^{\rm New}\left(U(1)_{B-L}\right)\\
&= -3+(4)+(4)+(-5)=0\,.
\end{aligned}$$

- To break the $U(1)_{B-L}$ gauge symmetry via the Higgs mechanism, we introduce two singlet scalars ϕ_1 and ϕ_8, with $B-L$ charges of -1 and $+8$
- In addition, we also introduce another scalar ϕ_{DM}, and its stability is ensured by appropriate choice of $B-L$ charge

Particle content

	Field	$SU(2)_L \times U(1)_Y$	$U(1)_{B-L}$
Fermions	$Q_L \equiv (u, d)_L^T$	$(\mathbf{2}, 1/6)$	$1/3$
	u_R	$(\mathbf{1}, 2/3)$	$1/3$
	d_R	$(\mathbf{1}, -1/3)$	$1/3$
	$\ell_L \equiv (\nu, \ e)_L^T$	$(\mathbf{2}, -1/2)$	-1
	e_R	$(\mathbf{1}, -1)$	-1
	N_{1R}	$(\mathbf{1}, 0)$	-4
	N_{2R}	$(\mathbf{1}, 0)$	-4
	N_{3R}	$(\mathbf{1}, 0)$	$+5$
Scalars	H	$(\mathbf{2}, 1/2)$	0
	ϕ_{DM}	$(\mathbf{1}, 0)$	n_{DM}
	ϕ_1	$(\mathbf{1}, 0)$	-1
	ϕ_8	$(\mathbf{1}, 0)$	8

Table: Particle spectrum and their charges of the proposed $U(1)_{B-L}$ model.

Model description

- The Yukawa interaction for the present model is given by

$$\mathcal{L}_{\rm Yuk} = Y_u \overline{Q}_L \widetilde{H} u_R + Y_d \overline{Q}_L H\, d_R + Y_e \overline{\ell}_L H e_R + \sum_{\alpha=1,2} h_{\alpha 3}\phi_1 \overline{N}^c_{\alpha R} N_{3R} + \sum_{\alpha,\beta=1,2} h_{\alpha\beta}\phi_8 \overline{N}^c_{\alpha R} N_{\beta R}.$$

- The scalar potential of the model is

$$V(H,\phi_{\rm DM},\phi_1,\phi_8) = \mu_{\rm H}^2 H^\dagger H + \lambda_{\rm H}(H^\dagger H)^2 + \mu_1^2\phi_1^\dagger\phi_1 + \lambda_1(\phi_1^\dagger\phi_1)^2 + \mu_8^2\phi_8^\dagger\phi_8 + \lambda_8(\phi_8^\dagger\phi_8)^2 + \mu_{\rm DM}^2\phi_{\rm DM}^\dagger\phi_{\rm DM} + \lambda_{\rm DM}(\phi_{\rm DM}^\dagger\phi_{\rm DM})^2 + \lambda_{\rm H1}(H^\dagger H)(\phi_1^\dagger\phi_1) + \lambda_{\rm H8}(H^\dagger H)(\phi_8^\dagger\phi_8) + \lambda_{18}(\phi_1^\dagger\phi_1)(\phi_8^\dagger\phi_8) + \lambda_{\rm HD}(H^\dagger H)(\phi_{\rm DM}^\dagger\phi_{\rm DM}) + \lambda_{\rm D1}(\phi_{\rm DM}^\dagger\phi_{\rm DM})(\phi_1^\dagger\phi_1) + \lambda_{\rm D8}(\phi_{\rm DM}^\dagger\phi_{\rm DM})(\phi_8^\dagger\phi_8).$$

- VEVs of different scalars are $\langle H\rangle = (0, v/\sqrt{2})^T$, $\langle\phi_1\rangle = v_1/\sqrt{2}$, and $\langle\phi_8\rangle = v_8/\sqrt{2}$. The DM field $\phi_{\rm DM} = \frac{(S+iA)}{\sqrt{2}}$ doesn't acquire any VEV.
- Mass of DM $\Longrightarrow$ $M_{\rm DM}^2 = \mu_{\rm DM}^2 + \frac{\lambda_{\rm HD}}{2}v^2 + \frac{\lambda_{\rm D1}}{2}v_1^2 + \frac{\lambda_{\rm D8}}{2}v_8^2$.
- We consider $\lambda_{\rm H1},\ \lambda_{\rm H8} = 0 \Longrightarrow M_h = \sqrt{2\lambda_{\rm H} v^2} = 125$ GeV.

Mixing in scalar spectrum

- Scalar fields ϕ_1 and ϕ_8 are parametrized as

$$\phi_{1,8}^0 = \frac{1}{\sqrt{2}}(v_{1,8} + h_{1,8}) + \frac{i}{\sqrt{2}} A_{1,8}$$

- Considering non-zero mixing between ϕ_1 and ϕ_8, the mass matrix in (h_1, h_8) basis is

$$\mathcal{M}_0^2 = \begin{pmatrix} 2\lambda_1 v_1^2 & \lambda_{18} v_1 v_8 \\ \lambda_{18} v_1 v_8 & 2\lambda_8 v_8^2 \end{pmatrix}.$$

- After diagonalization, with $\tan 2\alpha = \dfrac{\lambda_{18} v_1 v_8}{(\lambda_8 v_8^2 - \lambda_1 v_1^2)}$ the obtained mass eigenstates denoted by H_1, H_2 satisfy

$$h_1 = H_1 \cos\alpha + H_2 \sin\alpha, \quad h_8 = -H_1 \sin\alpha + H_2 \cos\alpha.$$

Stability of scalar dark matter

- No ad-hoc symmetry is assumed to stabilize DM
- Rather the model structure itself does it, i.e., $n_{\rm DM} = \pm 4, \pm 5$ and fractional charges forbids the following decay channels .

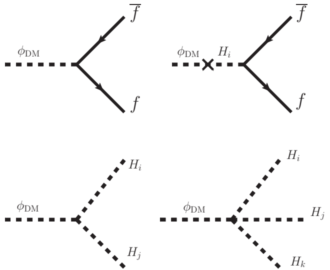


Figure: Figures in top panel $\Rightarrow n_{DM} \neq 0$,
bottom-left panel $\Rightarrow n_{DM} \neq \pm 2, \pm 7, \pm 9, \pm 16$,
bottom-right panel $\Rightarrow n_{DM} \neq \pm 1, \pm 3, \pm 6, \pm 8, \pm 10$

Relic abundance

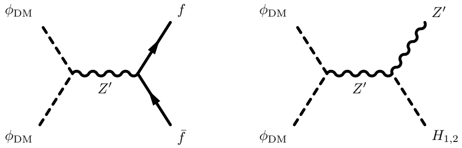


Figure: Feynman diagrams relevant in DM observables.

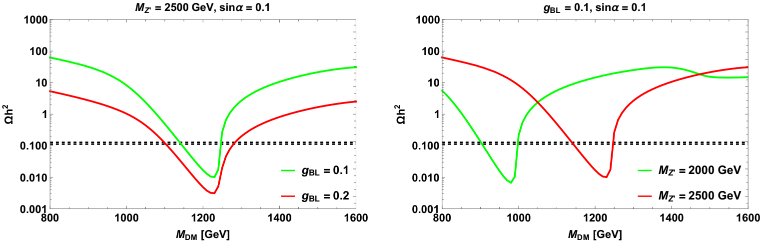
- DM relic density is calculated in the Z' portal

$$\Omega h^2 = \frac{2.14 \times 10^9 \mathrm{GeV}^{-1}}{g *^{1/2} M_{Pl}} \frac{1}{J(x_f)}, \qquad J(x_f) = \int_{x_f}^{\infty} \frac{\langle \sigma v \rangle (x)}{x^2} dx.$$

Parameters	$n_{\rm DM}$	M_{H_1} [GeV]	M_{H_2} [GeV]	v_1 [GeV]
Values	4	600	1000	1000

Table: Fixed parameters for Z'-mediated DM observables.

- Relevant parameters : $M_{Z'}, g_{\rm BL}, M_{\rm DM}, \alpha$



Packages: CalcHEP, micrOMEGAs

Limits on WIMP-nucleon cross section

The effective Lagrangian follows as

$$i\mathcal{L}_{\rm eff} \supset -\frac{n_{\rm DM} g_{\rm BL}^2}{3M_{Z'}^2}\left(S\partial^\mu A - A\partial^\mu S\right)\bar{u}\gamma_\mu u - \frac{n_{\rm DM} g_{\rm BL}^2}{3M_{Z'}^2}\left(S\partial^\mu A - A\partial^\mu S\right)\bar{d}\gamma_\mu d.$$

The DM-nuclei SI contribution is given by

$$\sigma_{\rm SI}^{\rm N} = \frac{1}{16\pi}\left(\frac{M_{\rm N} M_{\rm DM}}{M_{\rm N}+M_{\rm DM}}\right)^2 |A|^2 \frac{n_{\rm DM}^2 g_{\rm BL}^4}{M_{Z'}^4}.$$

The Z' mediated DM-nucleon SI contribution is given by

$$\sigma_{Z'} = \frac{\mu^2}{16\pi}\frac{n_{\rm DM}^2 g_{\rm BL}^4}{M_{Z'}^4}.$$

where $\mu = \left(\frac{M_n M_{\rm DM}}{M_n + M_{\rm DM}}\right)$ is the reduced mass of DM-nucleon system, M_n being the nucleon mass.

- Range of parameters : $M_{H_1} \sim (0.5-1)$ TeV, $M_{H_2} \sim (1-2)$ TeV, $\sin\alpha < 1$.

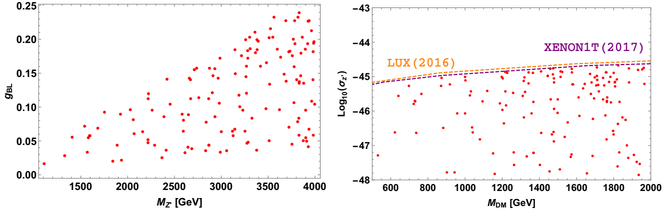
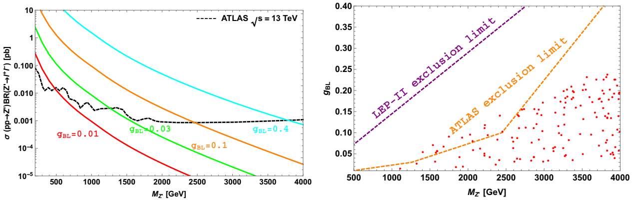


Figure: Left panel denotes the parameters space that satisfy the current relic density in 3σ range and XENON1T. The right panel depicts the WIMP-nucleon SI cross section with the mass of the scalar DM for the parameter space shown in the left panel.

ATLAS dilepton limits

ATLAS results from the study of dilepton signals ($ee, \mu\mu$) for the Z' boson provide the most stringent limits $M_{Z'} - g_{\rm BL}$ parameter space.



* We still have a decent space for the model parameters that meet all the constraints on DM observables and collider limits.

[LEP Electroweak Collaboration, Phys.Rept. **532** (2013) 119-244.

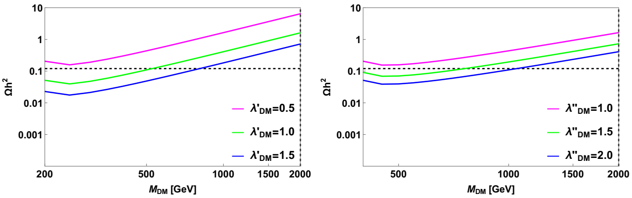
The ATLAS collaboration, ATLAS-CONF-2015-070.]

Semi-annihilation

For $n_{\rm DM} = 1/3$ there is a quartic term in the Lagrangian is of the form $\frac{\lambda'_{\rm DM}}{3}\phi^3_{\rm DM}\phi_1$ and for $n_{\rm DM} = 8/3$, a term of $\frac{\lambda''_{\rm DM}}{3}\phi^3_{\rm DM}\phi_8$ is allowed.

$$\hat{\sigma}_{1/3} = \frac{\lambda'^2_{\rm DM}}{64\pi s}\frac{\left[(s-(M_{\rm DM}+M_{H_1})^2)(s-(M_{\rm DM}-M_{H_1})^2)\right]^{\frac{1}{2}}}{\left[s(s-4M^2_{\rm DM})\right]^{\frac{1}{2}}},$$

$$\hat{\sigma}_{8/3} = \frac{\lambda''^2_{\rm DM}}{64\pi s}\frac{\left[(s-(M_{\rm DM}+M_{H_2})^2)(s-(M_{\rm DM}-M_{H_2})^2)\right]^{\frac{1}{2}}}{\left[s(s-4M^2_{\rm DM})\right]^{\frac{1}{2}}}.$$



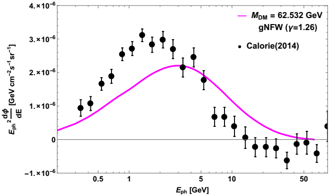
- $M_{H_1} = 200$ GeV and $M_{H_2} = 400$ GeV.

GC gamma ray excess

The excess in γ-ray emission from the GC region can be explained with the Higgs portal channels maximally annihilating to $b\bar{b}$

$$\frac{d\Phi_{ph}}{d\Omega dE_{ph}} = \frac{\rho_\odot^2 r_\odot J}{8\pi M_{\rm DM}^2} \sum_f \langle \sigma v \rangle_f \frac{dN_{ph}^f}{dE_{ph}}, \quad J = \int_{l.o.s} \frac{1}{r_\odot} \left(\frac{\rho(r)}{\rho_\odot} \right)^2 ds.$$

Here $\rho_\odot = 0.4\ {\rm GeV cm^{-3}}$, $r_\odot = 8.5$ kpc and $\rho(r)_{\rm gNFW} = \frac{(r/r_c)^{-\gamma} \rho_\odot}{[1+(r/r_c)^\gamma]^{(3-\gamma)}}$ with $r_c = 20$ kpc.



Parameters			Observables		
M_h [GeV]	$M_{\rm DM}$ [GeV]	$\lambda_{\rm HD}$	Ωh^2	$\langle \sigma v \rangle$ [cm^{3}s^{-1}]	σ_h[pb]
125.	63.5	2×10^{-4}	0.13	4.07×10^{-26}	8.74×10^{-14}

Neutrino mass in Canonical seesaw

- No RH neutrinos to generate light neutrino mass by Type-I seesaw.
- Introducing a scalar doublet η with $B-L$ charge -3, and the Yukawa term becomes

$$\sum_{\alpha=1,2} Y_{i\alpha}\overline{(\ell_L)}_i\tilde{\eta}N_{\alpha R} + \sum_{\alpha,\beta=1,2} h_{\alpha\beta}\phi_8\overline{N^c_{\alpha R}}N_{\beta R} + \sum_{\alpha=1,2} h_{\alpha 3}\phi_1\overline{N^c_{3R}}N_{\alpha R} + \text{h.c.}$$

- The Yukawa matrix and the fermion mass matrix after SSB are:

$$Y = \begin{pmatrix} Y_{11} & Y_{12} & 0 \\ Y_{21} & Y_{22} & 0 \\ Y_{31} & Y_{32} & 0 \end{pmatrix}, \qquad M_R = \frac{1}{\sqrt{2}}\begin{pmatrix} h_{11}v_8 & h_{12}v_8 & h_{13}v_1 \\ h_{12}v_8 & h_{22}v_8 & h_{23}v_1 \\ h_{13}v_1 & h_{23}v_1 & 0 \end{pmatrix}.$$

- Choosing $h_{11} = h_{22} = h$, $h_{12} = 2h$, $h_{13} = h_{23} = 3h$ and $v_1 = v_8 = v'$, we obtain the mass eigenstates

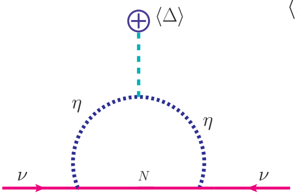
$$N^D_{1R} = \frac{1}{\sqrt{2}}(-N_{1R} + N_{2R}), \quad N^D_{2R} = \frac{1}{\sqrt{6}}(-N_{1R} - N_{2R} + 2N_{3R}), \quad N^D_{1R} = \frac{1}{\sqrt{3}}(N_{1R} + N_{2R} + N_{3R})$$

having masses $-(hv'/\sqrt{2})$, $-(3hv'/\sqrt{2})$ and $(6hv'/\sqrt{2})$.

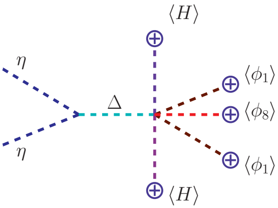
- So the total neutrino mass matrix in the $(\overline{\nu_{\alpha L}}, \overline{N^c_{\alpha R}})^T$ and $(\nu^c_{\alpha L}, N_{\alpha R})^T$ bases
$$M = \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix} ,$$
where $M_D = Y \langle \eta \rangle$ is the Dirac neutrino mass connecting $\nu_L - N_R$ and M_R is the Majorana mass.
- With block diagonalization, the light neutrino mass formula for canonical seesaw mechanism is
$$m_\nu = -M_D M_R^{-1} M_D^T .$$
- From the structure of the Yukawa matrix, it is clear that the light neutrino mass matrix generated in this manner will have a vanishing eigenvalue which corresponds to the scenario where the lightest neutrino being massless.

Radiative mechanism

- Light neutrino mass can also be generated via radiative mechanism with inclusion of inert doublet scalar η and scalar triplet Δ.
- This framework does not allow canonical seesaw mechanism as η can not take non-zero vacuum expectation value, being inert.



$$\langle\Delta\rangle = v_\Delta \simeq \frac{v^2 v_1^2 v_8}{\Lambda^2 M_\Delta^2}$$



Due to the inclusion of two extra scalars η and Δ, the additional contributions to the scalar potential are given as

$$V_{\rm Scalar} = (\mu_\eta^2|\eta|^2 + \lambda_\eta|\eta|^2) + \lambda_{H\eta}(\eta^\dagger\eta)(H^\dagger H) + \lambda'_{H\eta}(\eta^\dagger H)(H^\dagger\eta) + \mu_{\Delta\eta}((\eta^T\Delta^\dagger\eta) +$$
$$+ \sum_{i=1,8}\lambda_{\eta\phi_j}(\eta^\dagger\eta)(\phi_j^\dagger\phi_j) + \mu_\Delta^2{\rm Tr}[\Delta^\dagger\Delta] + \lambda_{\Delta1}{\rm Tr}[\Delta^\dagger\Delta]^2 + \lambda_{\Delta2}{\rm Tr}[(\Delta^\dagger\Delta)^2]$$
$$+ {\rm Tr}[\Delta^\dagger\Delta][\lambda_{\Delta H}(H^\dagger H) + \lambda_{\Delta\eta}(\eta^\dagger\eta) + \sum_{j=1,2}\lambda_{\Delta\phi_i}(\phi_j^\dagger\phi_j)].$$

The mass splitting between the real and imaginary parts of the mass of $\eta = (\eta_R + i\eta_I)/\sqrt{2}$ is

$$M_{\eta_R}^2 - M_{\eta_I}^2 = 2\sqrt{2}\mu_{\Delta\eta}v_\Delta\ , \tag{2}$$

where v_Δ is the induced VEV of the neutral component of Δ, whose value is constrained from the electroweak ρ parameter through the relation

$$\rho = \frac{1 + \frac{2v_\Delta^2}{v^2}}{1 + \frac{4v_\Delta^2}{v^2}}\ . \tag{3}$$

- The measured value ρ parameter $\rho = 1.00040 \pm 0.00024$ imposes strict bound on $v_\Delta \leq 2\text{GeV}$.
- Such small induced VEV can not be generated naturally, so considering the higher dimensional operators of the form $\frac{1}{\Lambda^2}(H^T \Delta^\dagger H)(\phi_8^\dagger \phi_1 \phi_1)$, which yields the VEV of the neutral component of Δ as

$$\langle \Delta^0 \rangle = v_\Delta \simeq \frac{v^2 v_1^2 v_8}{\Lambda^2 M_\Delta^2}.$$

Thus, the light neutrino mass can be generated at one-loop level as

$$(m_\nu)_{ij} = \frac{Y_{ik} Y_{jk}}{16\pi^2} \left(\frac{m_{\eta_R}^2}{m_{\eta_R}^2 - M_{R_k}^2} \ln \frac{m_{\eta_R}^2}{M_{R_k}^2} - \frac{m_{\eta_I}^2}{m_{\eta_I}^2 - M_{R_k}^2} \ln \frac{m_{\eta_I}^2}{M_{R_k}^2} \right) ,$$

where M_{R_k} $(k = 1, 2)$, is the mass of the exotic fermion. If we assume $m_{\eta_R}^2 + m_{\eta_I}^2 \approx M_{R_k}^2$, then

$$(m_\nu)_{ij} = \frac{M_{\eta_R}^2 - M_{\eta_I}^2}{32\pi^2} \frac{Y_{ik} Y_{jk}}{M_{Rk}} .$$

Thus, the light neutrino mass matrix becomes

$$m_\nu = \frac{\sqrt{2}}{16\pi^2} \mu_{\Delta\eta} v_\Delta Y M_R^{-1} Y^T = \frac{\sqrt{2}\mu_{\Delta\eta}}{16\pi^2} \frac{v^2 v_1^2 v_8}{\Lambda^2 M_\Delta^2} Y M_R^{-1} Y^T.$$

Conclusion

- We the scalar dark matter phenomenology in the context of $U(1)_{B-L}$ extension of SM where three heavy exotic fermions with $B-L$ charges $-4, -4$ and $+5$ are added to make the model anomaly free.
- Two scalar singlets with $B-L$ charges -1 and $+8$ are introduced break the $B-L$ gauge symmetry and also to generate the mass terms for the exotic fermions and the new gauge boson Z'.
- A scalar singlet $\phi_{\rm DM}$ is introduced such that the $U(1)_{B-L}$ symmetry takes care of making it a stable dark matter candidate.
- Scalar DM phenomenology has been explored in the prospects of gauge mediated channels.
- A viable parameter space is shown consistent with the current dark matter experimental limits by PLANCK on relic density, direct limits from XENON1T and also the ATLAS dilepton constraints.
- The indirect signals of the excess in photon flux from the galactic center has been revisited in the light of Higgs mediated annihilation channels.
- Light neutrino mass can be generated by Canonical and Radiative mechanism by adding a scalar triplet and an inert doublet to the model.

Thank you