Relativistic Freeze-in with Scalar Dark Matter in Gauged B-L Model and Electroweak Symmetry Breaking.

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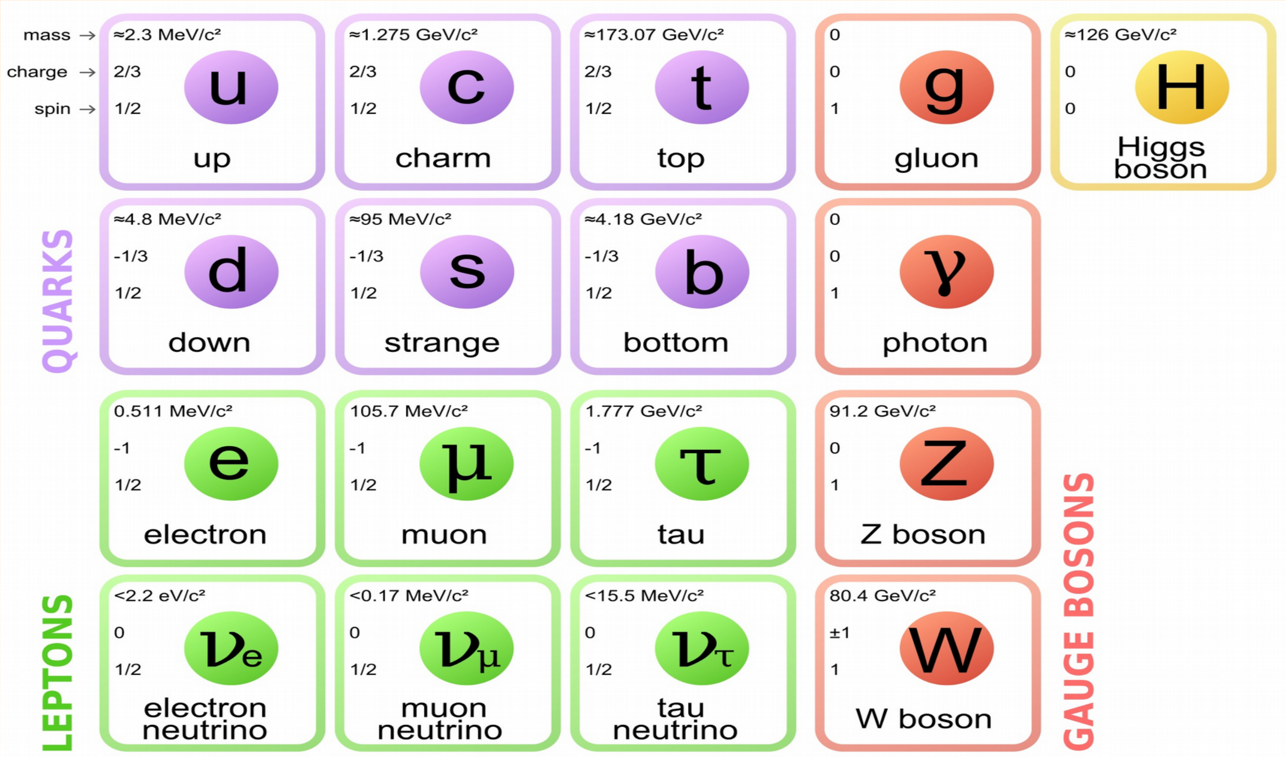
Based on work done with Priyotosh Bandyopadhyay, Manimala Mitra (**arXiv:2012.07142**)

12th February, 2021.

Talk Plan

- **Introduction**
- **$U(1)_{B-L}$ model**
- **Results based on $U(1)_{B-L}$ model**
- **Conclusion**

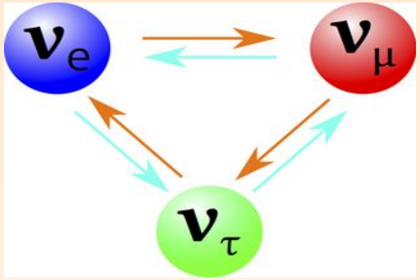
The Standard Model



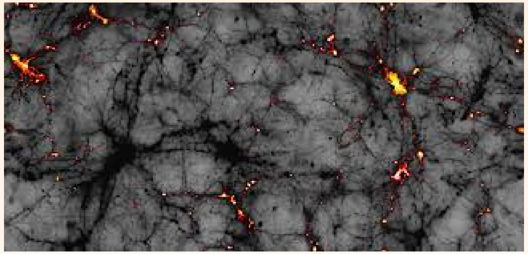
LHC results able to confirm the validity of the SM, with no signatures of new physics.

Problems in the SM

- SM fails to explain neutrino mass and mixings.



- SM doesn't have DM candidate.



- SM fails to explain observed baryon asymmetry.

Who can be a DM ?

- Should be massive
- Should be electrically neutral
- Should be present in early universe
- Should be stable or at least with half life greater than the age of the universe

Need a symmetry

Singlet Scalar

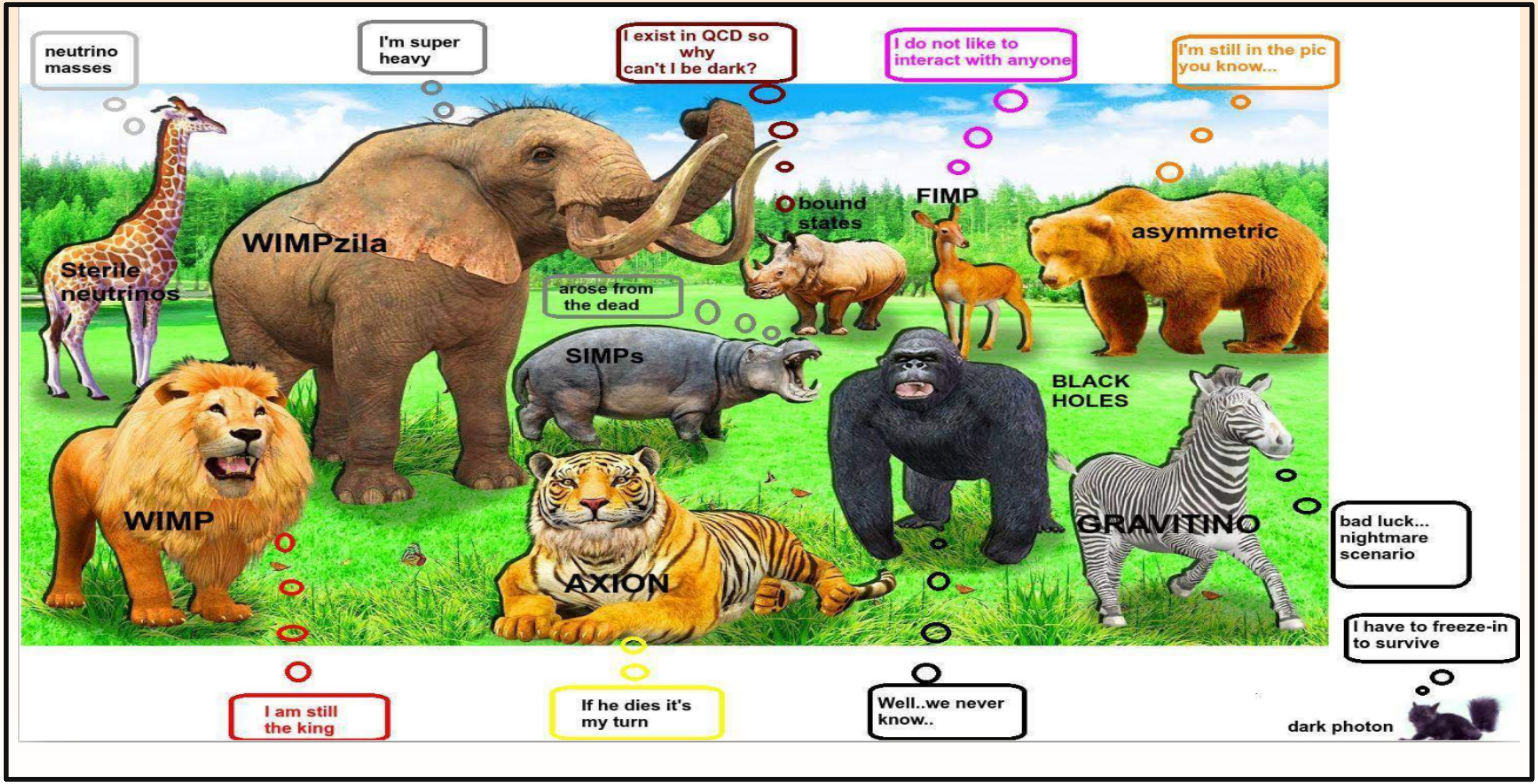
Singlet Fermion

Scalar in triplet repn

Fermion in triplet repn

...and many more

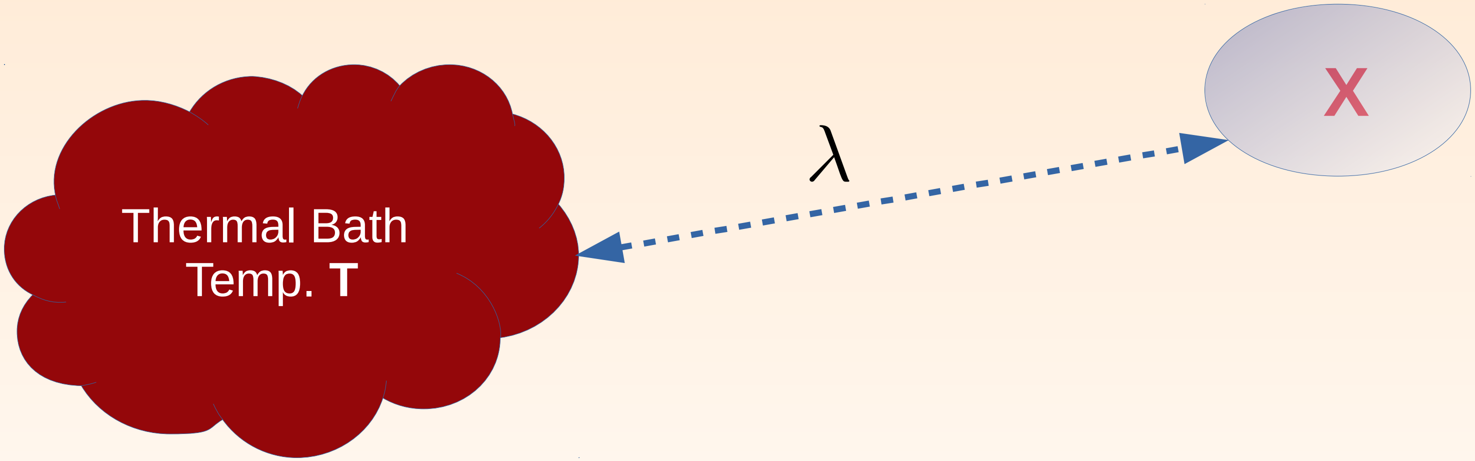
Zoo of Dark Matter Candidates



Freeze-in Mechanism Overview

- Freeze-in is relevant for particles that are feeble coupled.

Feeble **I**nteracting **M**assive **P**article(**FIMPs**) **X**



- Although interactions are feeble they lead to some X production.
- Increasing the interaction strength increases the yield opposite to Freeze out mechanism.
- FIMP never reaches thermal equillibrium because of suppressed interaction.

$U(1)_{B-L}$ to explain DM and neutrino mass

New Particles

Gauge Group	Baryon Fields			Lepton Fields			Scalar Fields		
	$Q_L^i = (u_L^i, d_L^i)^T$	u_R^i	d_R^i	$L_L^i = (\nu_L^i, e_L^i)^T$	e_R^i	N_R^i	Φ	$\mathcal{S}$	ϕ_D
$SU(2)_L$	2	1	1	2	1	1	2	1	1
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	0	1/2	0	0
$U(1)_{B-L}$	1/3	1/3	1/3	−1	−1	−1	0	2	q_{DM}

B-L charges for all the fields present in the model.

Free paramter but choice of its decide whether DM will be FIMP or WIMP

The complete Lagrangian for the model:-

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - \frac{1}{4}F_{BL\mu\nu}F_{BL}{}^{\mu\nu} + \frac{i}{2}\bar{N}_i\gamma^\mu D_\mu N_i - V(\Phi,\mathcal{S})$$
$$\left(\sum_{i=1}^{3}\lambda_{NS}\mathcal{S}\bar{N}_i^c N_i + \sum_{i,j=1}^{3} y'_{N,ij}\bar{L}_i\tilde{\Phi}N_j + h.c.\right)$$

$$V(\Phi,\mathcal{S}) = \mu_S^2\mathcal{S}^\dagger\mathcal{S} + \mu_h^2\Phi^\dagger\Phi + \lambda_S(\mathcal{S}^\dagger\mathcal{S})^2 + \lambda_h(\Phi^\dagger\Phi)^2 + \lambda_{Sh}(\Phi^\dagger\Phi)(\mathcal{S}^\dagger\mathcal{S})$$

$$\mathcal{L}_{DM} = (D^\mu\phi_D)^\dagger(D_\mu\phi_D) - \mu_D^2(\phi_D^\dagger\phi_D) - \lambda_D\,(\phi_D^\dagger\phi_D)^2 - \lambda_{Dh}\,(\phi_D^\dagger\phi_D)(\Phi^\dagger\Phi)$$
$$-\lambda_{SD}\,(\phi_D^\dagger\phi_D)(\mathcal{S}^\dagger\mathcal{S})$$

$$D_\mu X = (\partial_\mu + i\,g_{BL}\,Y_{B-L}(X)\,Z_{BL\mu})X$$

Gauge coupling (g_{BL})   **B-L charge** (Y_{B-L})

$B - L$ symmetry breaks spontaneously when $\mathcal{S}$ takes VEV

$\mu_h^2, \mu_S^2 < 0$ and $\mu_D^2 > 0$ → Ground state is defined as $<\Phi>=\frac{v}{\sqrt{2}}, <\mathcal{S}>=\frac{v_{BL}}{\sqrt{2}}$ and $<\phi_D>=0$

After symmetry breaking, Φ and $\mathcal{S}$ takes following form,

$$\Phi = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \qquad \mathcal{S} = \frac{v_{BL}+S}{\sqrt{2}}.$$

Owing to non-zero λ_{Sh} term and $v, v_{BL} \neq 0$, $\mathcal{S}$ and h mix after EWSB,

$$h_1 = h\cos\alpha + S\sin\alpha,$$
$$h_2 = -h\sin\alpha + S\cos\alpha.$$

***Neutrino masses*:-**

$$m^{\nu}_{ij} = \frac{y'_{N,ik} y'_{N,kj} < \Phi^2 >}{m_{N,k}}$$

Light SM neutrino masses is generated by Type-I seesaw mechanism.

$$m_{N,k} = \lambda_{NS} \langle \mathcal{S} \rangle$$ **(Majorana masses of the RHN's)**

Additional gauge boson from $U(1)_{B-L}$ is represented by Z_{BL} .

U(1) $_{B\text{-}L}$ ***gauge boson mass(*** Z_{BL} ***):-***

$$m_{Z_{\rm BL}} = 2 g_{BL} v_{BL}$$

mass is generated due to SSB of the *B-L* gauge symmetry

In our work, we have consider mass of $Z_{B\text{-}L}$ to be 5.5 TeV, which is in agreement with the LHC search for a massive resonance decaying into di-lepton final states.

Dark Matter(DM) Mass:-

$$m_{\phi_D}^2 = \mu_D^2 + \frac{\lambda_{Dh} v^2}{2} + \frac{\lambda_{SD} v_{BL}^2}{2}.$$

$\lambda_{SD}, \lambda_{Dh} \sim 10^{-10} - 10^{-13}$ → To accommodate ϕ_D as non-thermal DM

To a good approximation, we identify DM mass is governed by the bare mass term.

Stability of DM:- DM candidate ϕ_D has charge q_{DM} under $U(1)_{B-L}$

$$q_{DM} \neq \pm 2n \quad (n \in \mathbb{Z} \text{ and } n \leq 4)$$

→ ϕ_D can be the viable stable DM candidate

Thermal Corrections

- At high temperature, the scalar potential gets modified by the thermal corrections.
- Effect is captured by the thermal mass which amount to the replacements,

$$\mu_s^2 \to \mu_s^2 + c_s T^2 \quad , \quad \mu_h^2 \to \mu_h^2 + c_h T^2$$

$$V(\Phi, \mathcal{S}) = \mu_S^2 \mathcal{S}^\dagger \mathcal{S} + \mu_h^2 \Phi^\dagger \Phi + \lambda_S (\mathcal{S}^\dagger \mathcal{S})^2 + \lambda_h (\Phi^\dagger \Phi)^2 + \lambda_{Sh} (\Phi^\dagger \Phi)(\mathcal{S}^\dagger \mathcal{S})$$

where

$$c_h \simeq \frac{3}{16} g^2 + \frac{1}{16} g'^2 + \frac{1}{4} y_t^2 + \frac{1}{2} \lambda_h \ ,$$

$$c_s = \frac{1}{4} \lambda_s + \frac{1}{6} \lambda_{hs}$$

g, g' are the SM gauge couplings and y_t is top-quark Yukawa coupling.

Phase Transition: $(0,0)\to(0,v_{BL})\to(v_{ew},v_{BL})$

Transition to non- zero VEV's takes place at critical temperatures,

$$T_c^{v_{EW}} = \frac{|\mu_h|}{\sqrt{c_h}} ,$$

$$T_c^{v_{BL}} = \frac{|\mu_s|}{\sqrt{c_s}} ,$$

$$-\mu_h^2 = \frac{\lambda_{hs}}{4\lambda_s}\, m_s^2 + \frac{1}{2} m_h^2 ,$$

$$-\mu_s^2 = \frac{\lambda_{hs}}{4\lambda_h}\, m_h^2 + \frac{1}{2} m_s^2$$

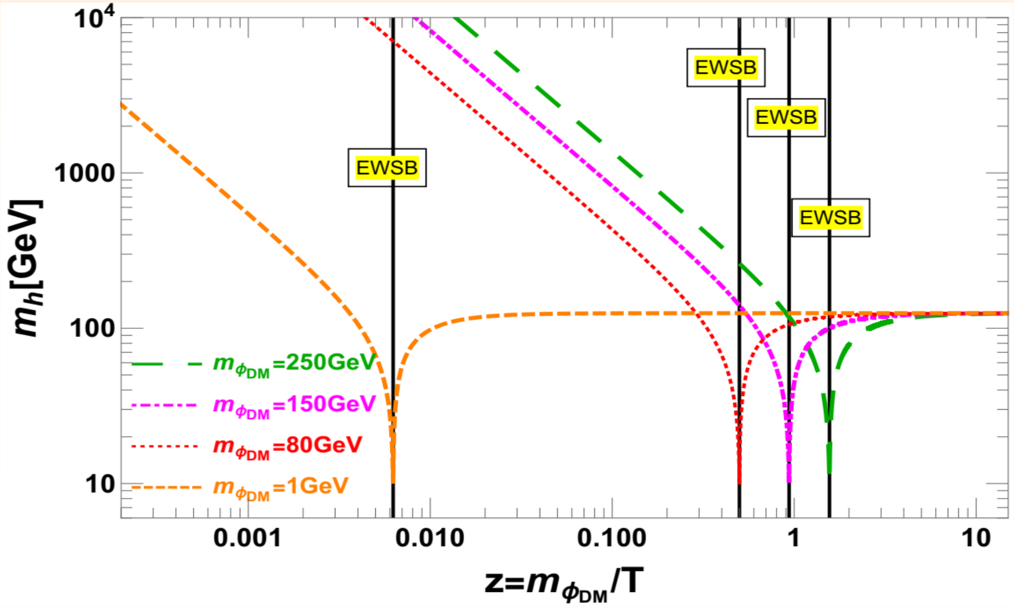
Neutrino thermal masses can be neglected as masses are suppressed by Y^2.

- $\mathcal{S}$ takes VEV v_{BL} and breaks $U(1)_{B-L}$ symmetry.
- Critical temperature of the $U(1)_{B-L}$ symmetry breaking is,

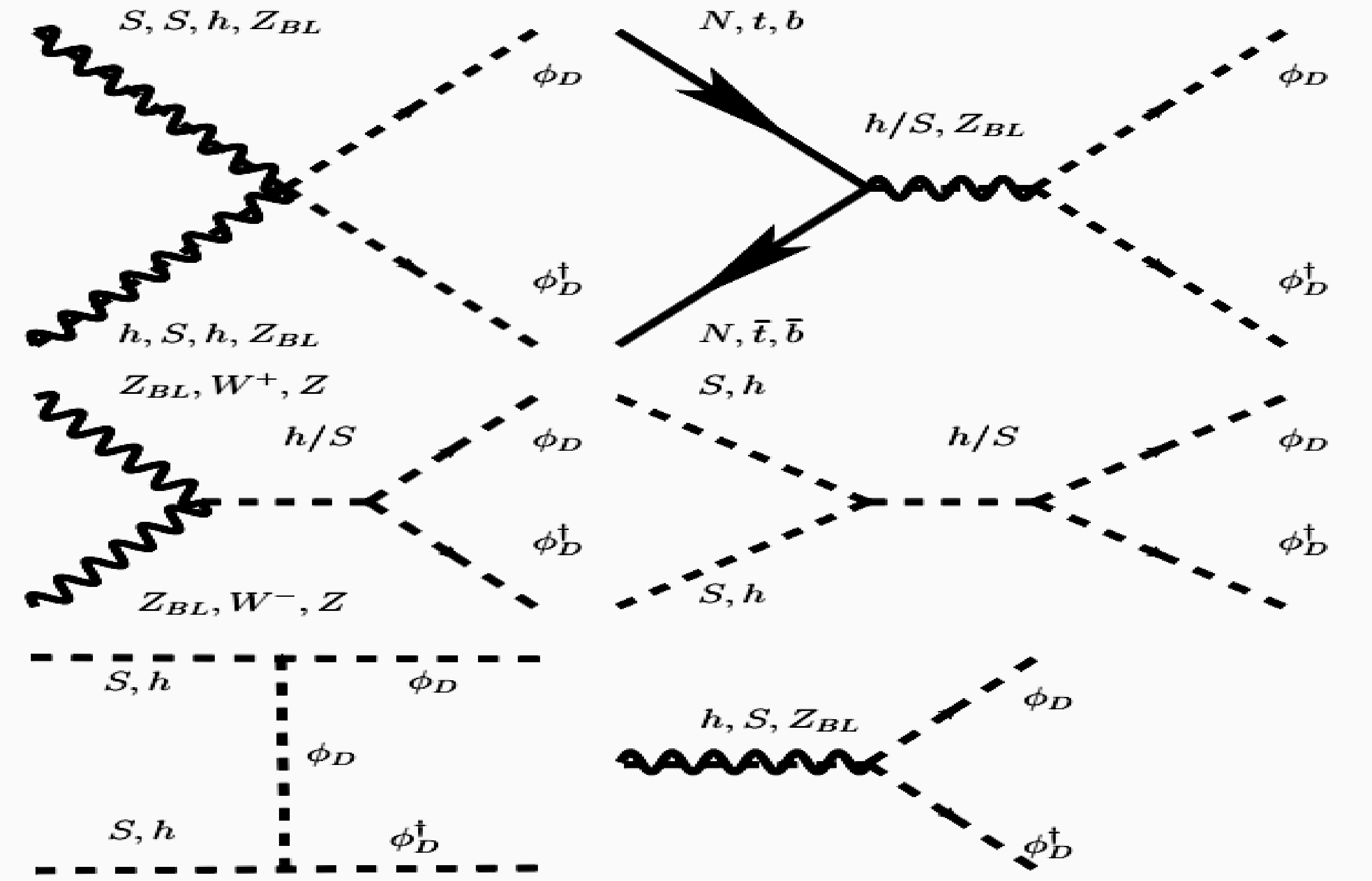
$$T_c^{v_{BL}} = \frac{|\mu_s|}{\sqrt{c_s}} \approx 2.4 \times 10^4 \ GeV$$

- We have assumed EWSB to be crossover in Higgs remain massive , i.e,

$$T_c^{v_{EW}} = \frac{|\mu_s h|}{\sqrt{c_h}} = 160 \ GeV, m_h = 10GeV$$



Possible production modes of ϕ_D



ϕ_D is gauged → thermalize → large g_{BL} coupling

↓

Only viable option to obtain the correct relic density is freeze-out.

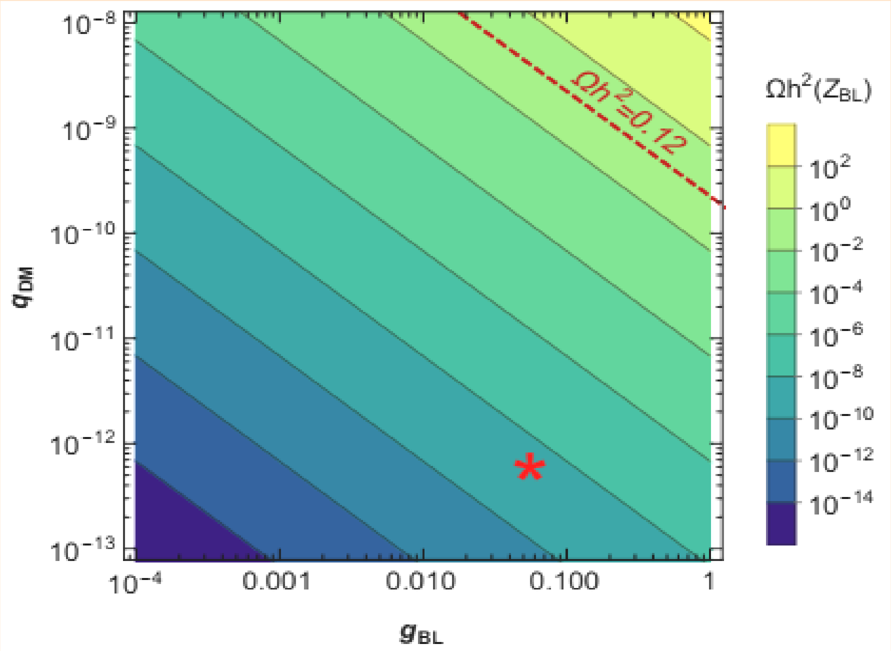
To study the possibility for the relativistic freeze-in compels us to choose very small q_{DM}.

The Boltzmann eqn. for the ϕ_D via gauge interaction is,

$$\frac{dY_{\phi_D}}{dz} = \frac{z^4}{s(m_{\phi_{DM}})H(m_{\phi_{DM}})}[\Gamma_{Z_{BL}\to\phi_D^*\phi_D} + \sum_{f=N,t,b}\Gamma_{\bar{f}f\to\phi_D^*\phi_D}].$$

The relic abundance of ϕ_D is given by,

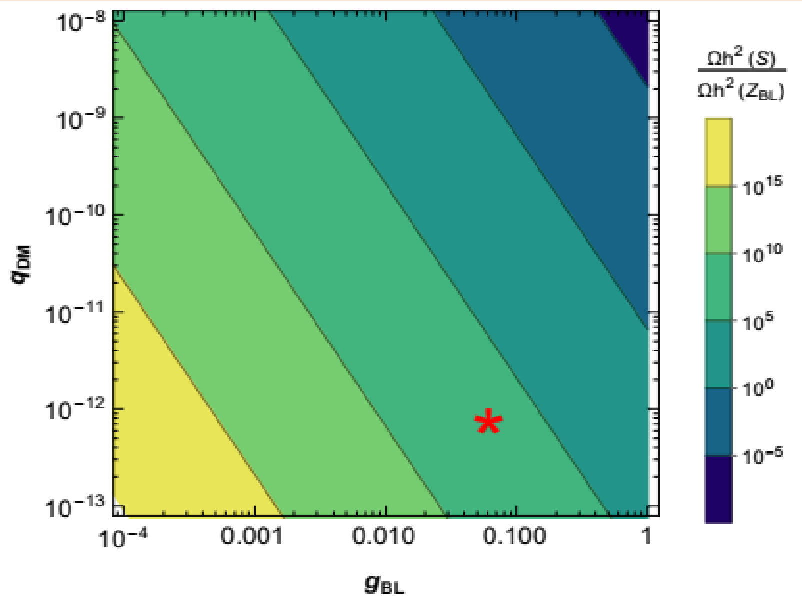
$$\Omega h^2(Z_{BL}) = \frac{m_{\phi_{DM}} s_0 Y_{\phi_D(\infty)}}{\rho_c/h^2}.$$



Parameters chosen are $m_{\phi_{DM}}$=1 GeV, $m_{Z_{BL}}$=5.5TeV, m_S=200 GeV

- For $q_{DM} > 10^{-10}$, production of DM through gauge interaction alone satisfy the relic density.
- With other possible production channels in our model will lead to overproduction of dark matter.

We choose $q_{DM} \approx 10^{-12}$ represented by the red star in our analysis such production from gauge interaction is negligible.

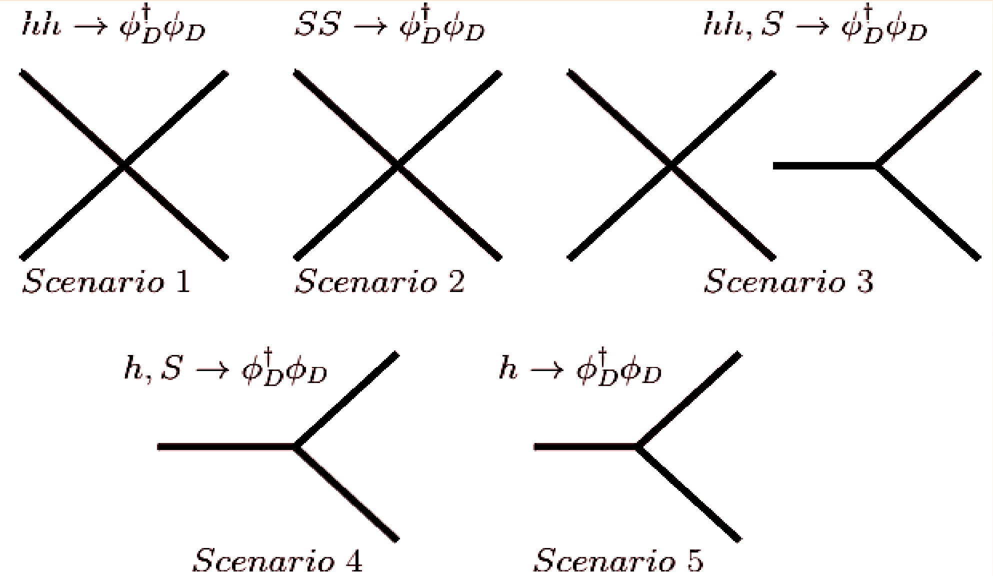


Parameters chosen are $m_{\phi_{DM}}$=1 GeV, $m_{Z_{BL}}$=5.5TeV, m_S=200 GeV

If decay of '*S*' is kinematically allowed, then production of DM from '*S*' decay starts to dominates compared to 'Z_{BL}' decay as we decrease q_{DM}.

$$\frac{\Gamma_{S\to\phi_D^*\phi_D}}{\Gamma_{Z_{BL}\to\phi_D^*\phi_D}} \propto \frac{\lambda_{SD}^2 m_{Z_{BL}}}{4g_{BL}^4 q_{DM}^2 m_S}$$

Different freeze-in scenarios depending on primary production mechanism.



The Boltzmann equation is given by,

$$\frac{dY_{\phi_D}}{dz} = \frac{z^4}{sH}\Big[(4-3\theta(z-z_{EW}))\Gamma_{hh\to\phi_D^\dagger\phi_D} + \Gamma_{SS\to\phi_D^\dagger\phi_D} + \Gamma_{NN\to\phi_D^\dagger\phi_D} + \Gamma_{S\to\phi_D^\dagger\phi_D} + \theta(z-z_{EW})\Big[\Gamma_{h\to\phi_D^\dagger\phi_D} + \Gamma_{hS\to\phi_D^\dagger\phi_D} + \\ + \Gamma_{W^+W^-\to\phi_D^\dagger\phi_D} + \Gamma_{ZZ\to\phi_D^\dagger\phi_D} + \Gamma_{b\bar{b}\to\phi_D^\dagger\phi_D} + \Gamma_{t\bar{t}\to\phi_D^\dagger\phi_D}\Big]\Big]$$

Relativistic Rates with the Bose-Einstien distribution and Fermi Dirac distribution func.

The reaction rate for $ab \to cd$ processes of incoming boson/fermions is,

$$\Gamma^{BE}_{2\to 2} = \frac{T}{4\pi^4}\int_0^\infty dE E^2 \int_0^\infty d\eta \frac{\sinh\eta}{e^{\frac{2E\cosh\eta}{T}}-1} \ln\left[\frac{\sinh\frac{(E+k_0)\cosh\eta+|k|\sinh\eta}{2T}}{\sinh\frac{(E+k_0)\cosh\eta-|k|\sinh\eta}{2T}}\frac{\sinh\frac{(E-k_0)\cosh\eta+|k|\sinh\eta}{2T}}{\sinh\frac{(E-k_0)\cosh\eta-|k|\sinh\eta}{2T}}\right] \times 4F\sigma^{CM}(E),$$

$$\Gamma^{FD}_{2\to 2} = \frac{T}{4\pi^4}\int_0^\infty dE E^2 \int_0^\infty d\eta \frac{\sinh\eta}{e^{\frac{2E\cosh\eta}{T}}-1} \ln\left[\frac{\cosh\frac{(E+k_0)\cosh\eta+|k|\sinh\eta}{2T}}{\cosh\frac{(E+k_0)\cosh\eta-|k|\sinh\eta}{2T}}\frac{\cosh\frac{(E-k_0)\cosh\eta+|k|\sinh\eta}{2T}}{\cosh\frac{(E-k_0)\cosh\eta-|k|\sinh\eta}{2T}}\right] \times 4F\sigma^{CM}(E).$$

At low temperature T limit,

$$\ln\left[\frac{\sinh\frac{(E+k_0)\cosh\eta+|k|\sinh\eta}{2T}}{\sinh\frac{(E+k_0)\cosh\eta-|k|\sinh\eta}{2T}}\frac{\sinh\frac{(E-k_0)\cosh\eta+|k|\sinh\eta}{2T}}{\sinh\frac{(E-k_0)\cosh\eta-|k|\sinh\eta}{2T}}\right] \approx \frac{2|k|\sinh\eta}{T},$$

$$\ln\left[\frac{\cosh\frac{(E+k_0)\cosh\eta+|k|\sinh\eta}{2T}}{\cosh\frac{(E+k_0)\cosh\eta-|k|\sinh\eta}{2T}}\frac{\cosh\frac{(E-k_0)\cosh\eta+|k|\sinh\eta}{2T}}{\cosh\frac{(E-k_0)\cosh\eta-|k|\sinh\eta}{2T}}\right] \approx \frac{2|k|\sinh\eta}{T}.$$

At the low temperature T limit, reaction rate is equal to the reaction rate obtained by MB distribution

$$\Gamma^{MB}_{2\to 2} = \frac{T}{4\pi^4}\int_{E_1^{min}}^{\infty} dE E|k| K_1\left(\frac{2E}{T}\right) 4F\sigma^{CM}(E).$$

Decay rate $(a \to bb)$

For the mother particle being fermion having mass M,

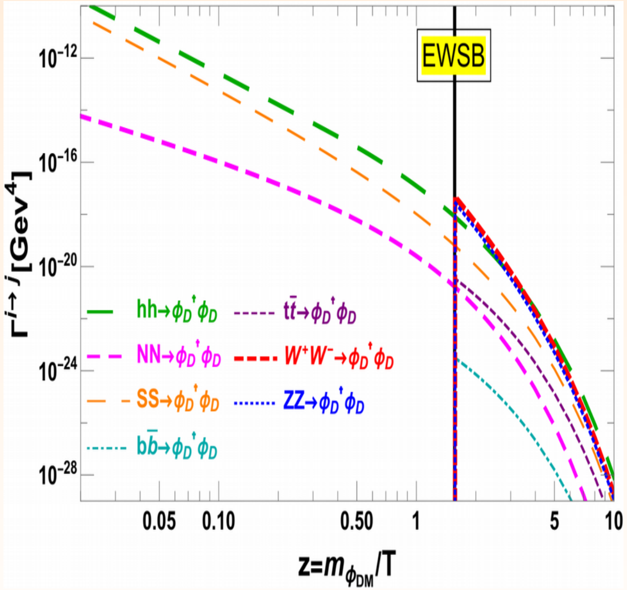
$$\Gamma^{FD}_{1\to 2} = \frac{\Gamma M^3}{2\pi^2}\int_1^{\infty} dt \frac{\sqrt{t^2-1}}{e^{\frac{M}{T}t}+1} \overset{\frac{M}{T}<<1}{\approx} \frac{\Gamma M^2 T}{2\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n} K_1\left(n\frac{M}{T}\right)$$

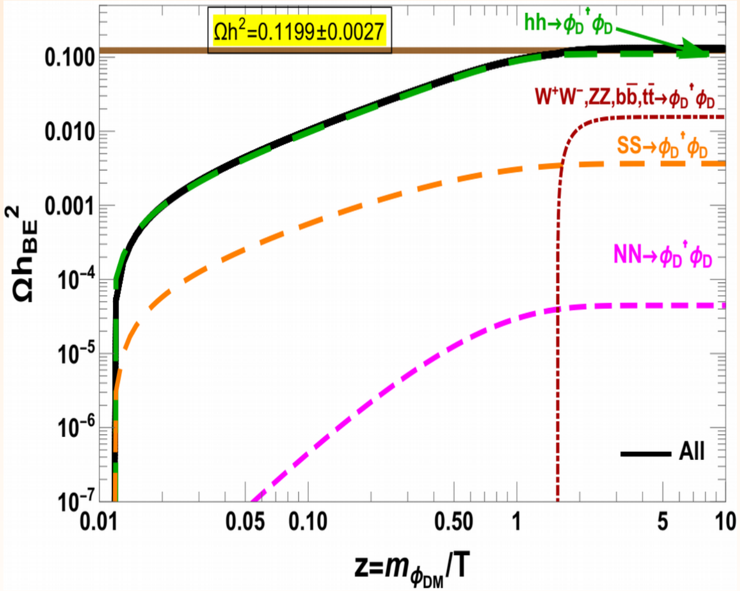
For the mother particle being boson having mass M,

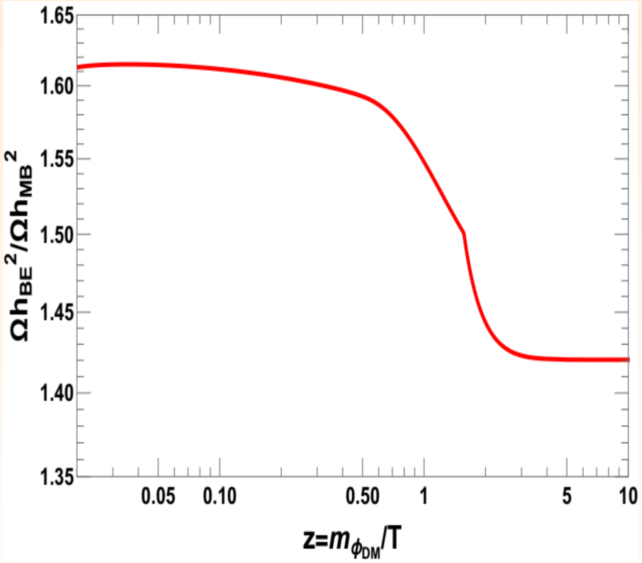
$$\Gamma^{BE}_{1\to 2} = \frac{\Gamma M^3}{2\pi^2}\int_1^{\infty} dt \frac{\sqrt{t^2-1}}{e^{\frac{M}{T}t}-1} \overset{\frac{M}{T}<<1}{\approx} \frac{\Gamma M^2 T}{2\pi^2}\sum_{n=1}^{\infty}\frac{1}{n} K_1\left(n\frac{M}{T}\right)$$

Freeze-in Scenario 1:- **(SM Higgs boson annhilation dominant)**

Scenario	Masses in GeV			Couplings				
	m_S	m_N	$m_{\phi_{DM}}$	y_N	λ_{SD}	λ_{Sh}	λ_{NS}	λ_{Dh}
1	200	300	250	10^{-7}	5.0×10^{-12}	6×10^{-6}	0.053	1.6×10^{-11}

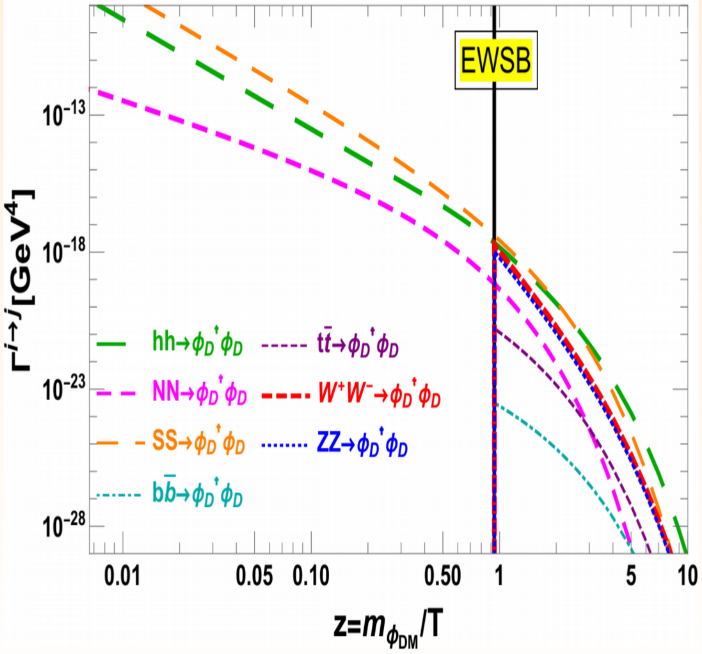


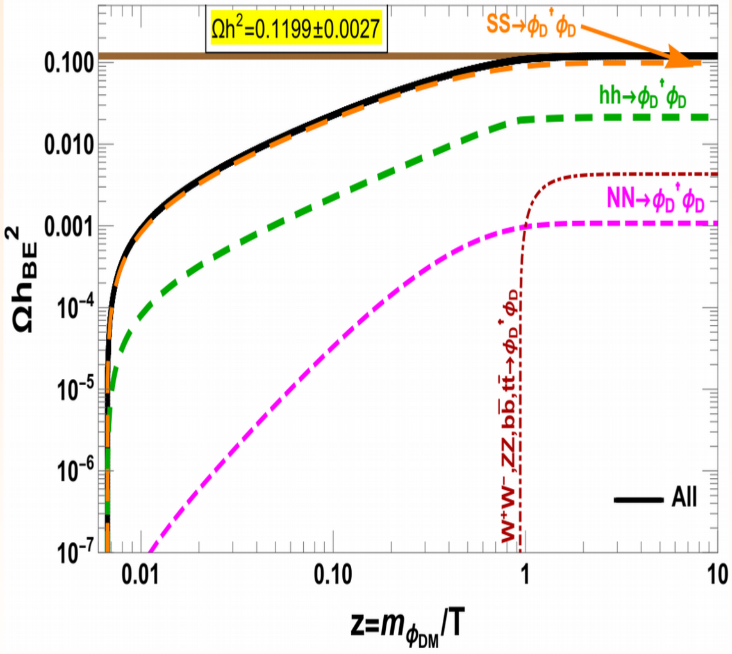


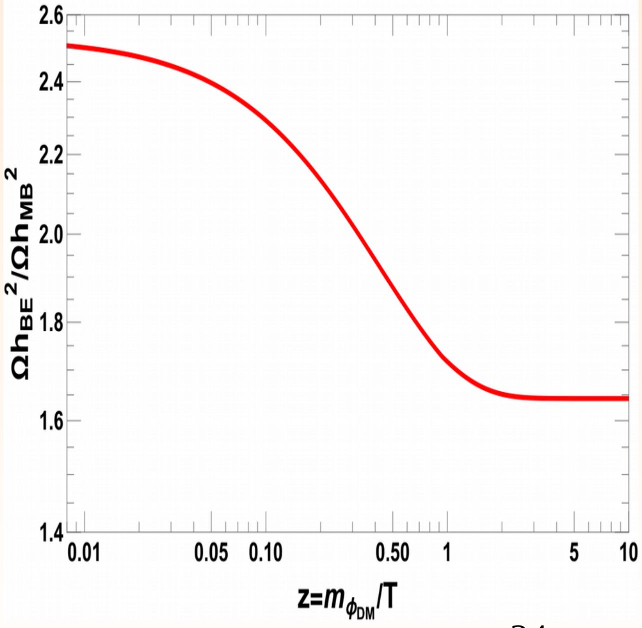


Freeze-in Scenario 2:- **(BSM Higgs boson annhilation dominant)**

Scenario	Masses in GeV			Couplings				
	m_S	m_N	$m_{\phi_{DM}}$	y_N	λ_{SD}	λ_{Sh}	λ_{NS}	λ_{Dh}
2	200	300	150	10^{-7}	3.0×10^{-11}	6×10^{-6}	0.053	7.5×10^{-12}

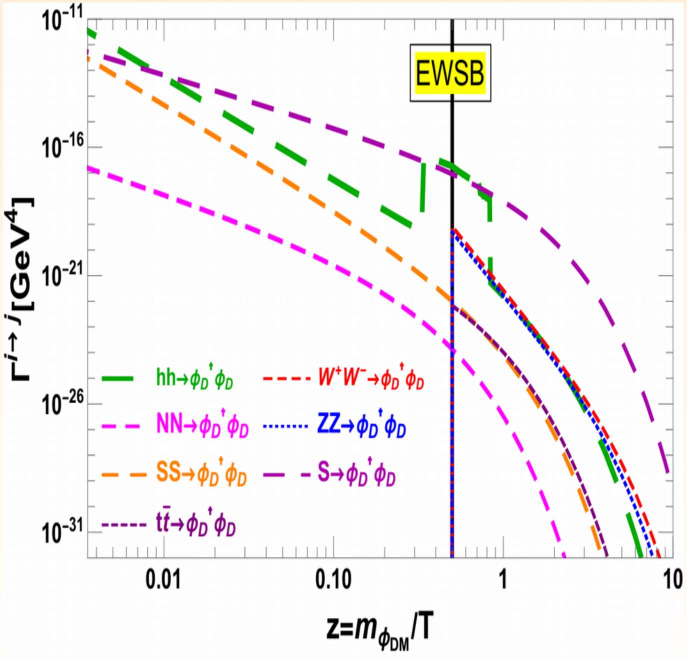


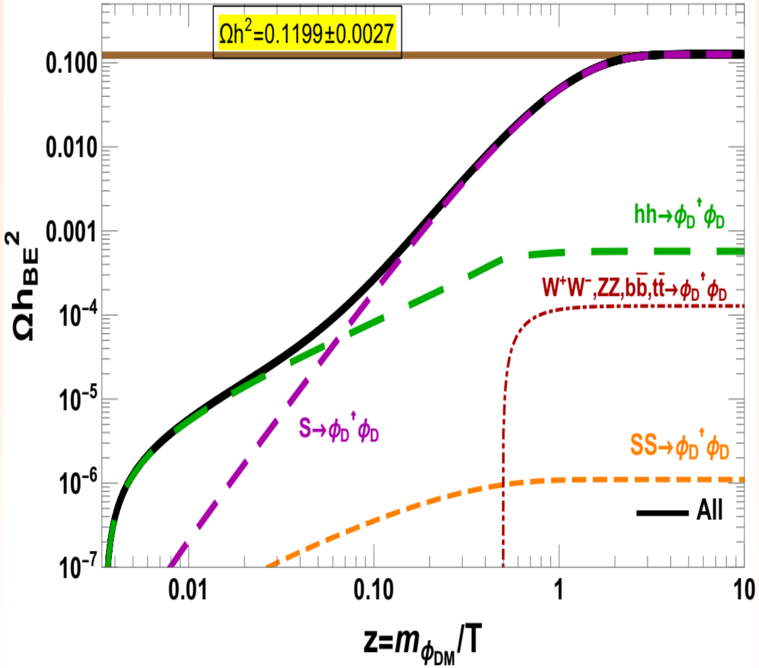


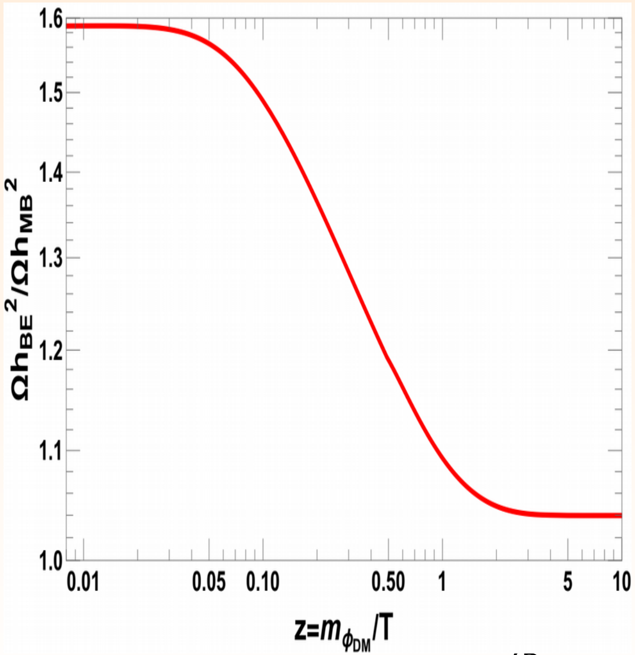


Freeze-in Scenario 3:- **(BSM Higgs boson decay dominant)**

Scenario	Masses in GeV			Couplings				
	m_S	m_N	$m_{\phi_{DM}}$	y_N	λ_{SD}	λ_{Sh}	λ_{NS}	λ_{Dh}
3	200	300	80	10^{-7}	1.28×10^{-13}	6×10^{-6}	0.053	1.414×10^{-12}

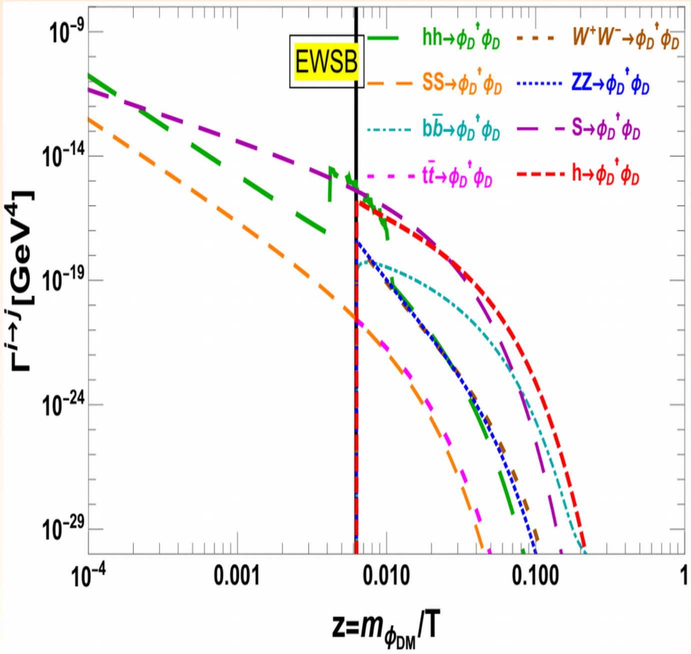


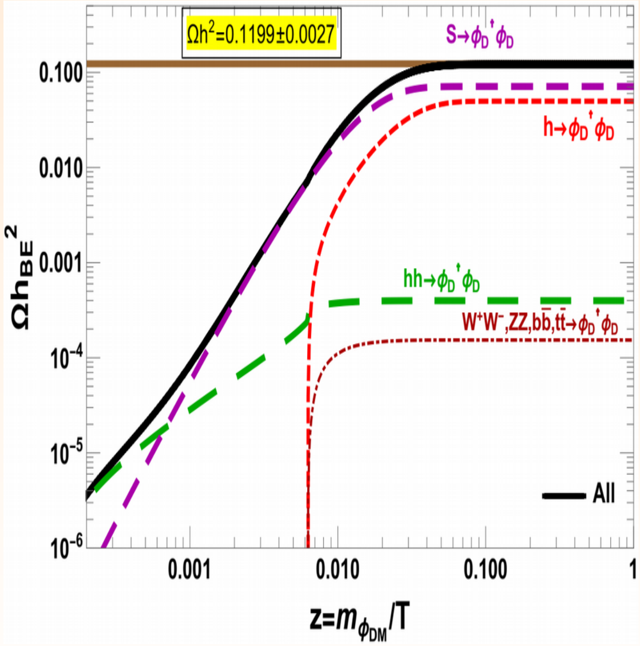


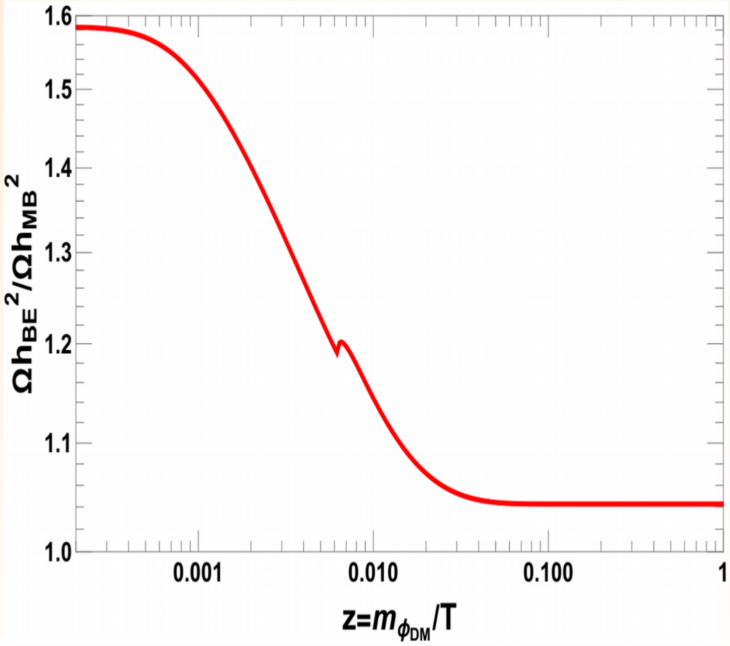


Freeze-in Scenario 4:- **(BSM Higgs boson decay dominant)**

Scenario	Masses in GeV			Couplings				
	m_S	m_N	$m_{\phi_{DM}}$	y_N	λ_{SD}	λ_{Sh}	λ_{NS}	λ_{Dh}
4	200	300	1	10^{-7}	6.65×10^{-13}	6×10^{-6}	0.053	8.6×10^{-12}

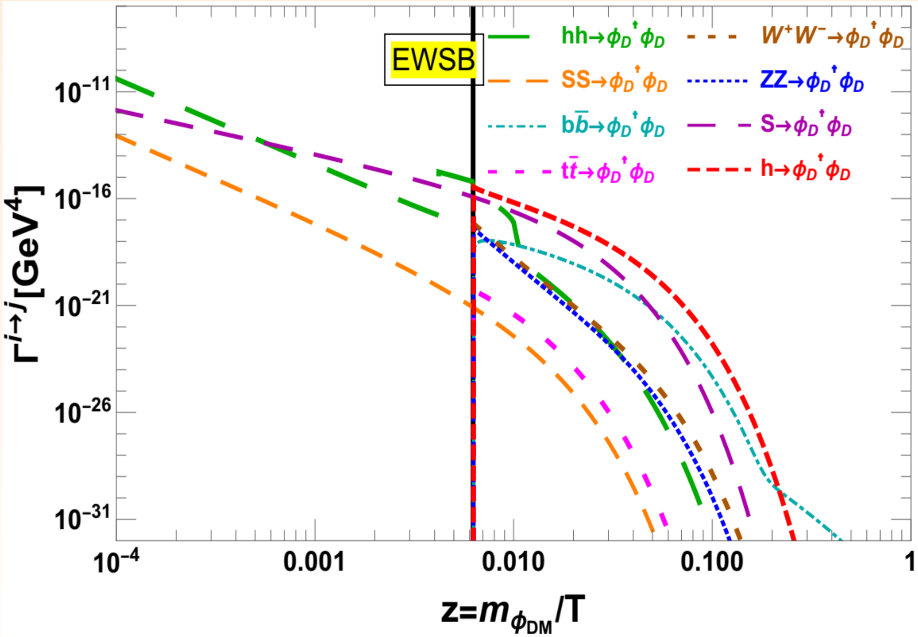


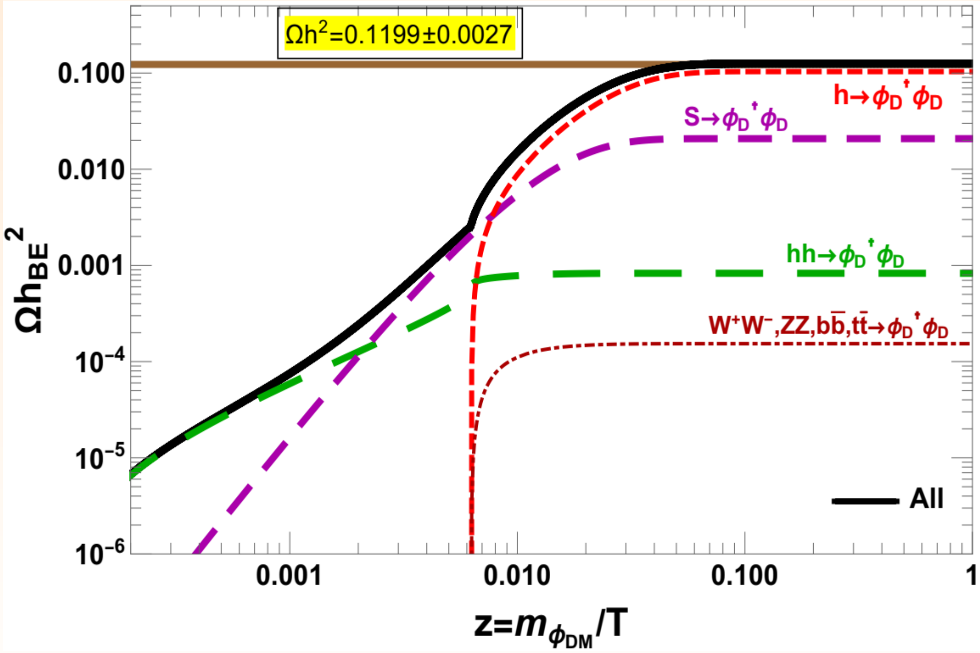


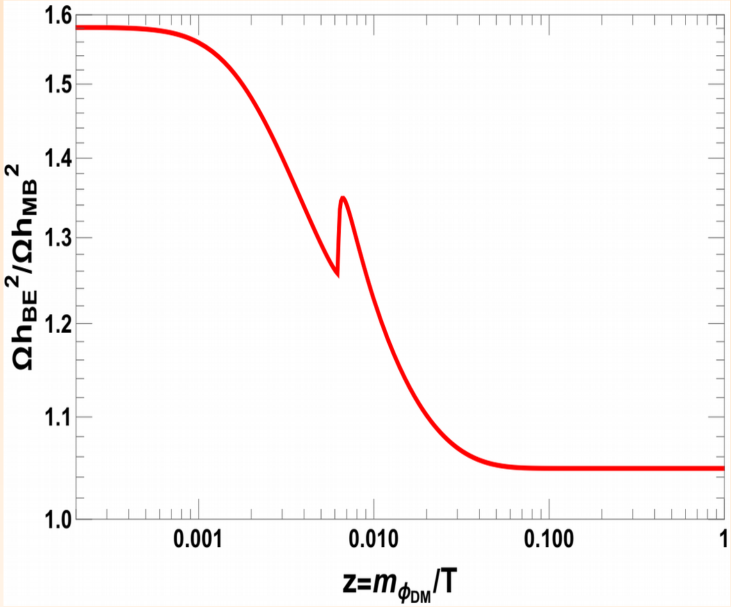


Freeze-in Scenario 5:- **(SM Higgs boson decay dominant)**

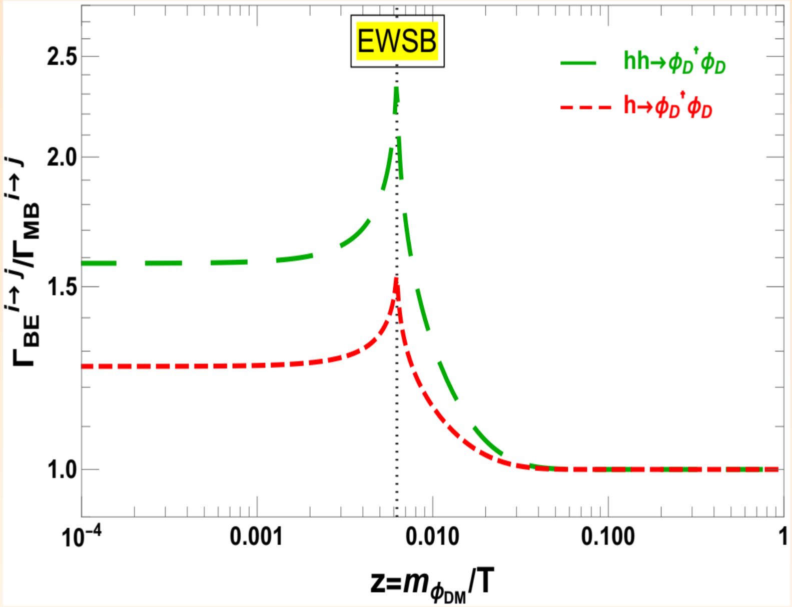
Scenario	Masses in GeV			Couplings				
	m_S	m_N	$m_{\phi_{DM}}$	y_N	λ_{SD}	λ_{Sh}	λ_{NS}	λ_{Dh}
5	200	300	1	10^{-7}	3.6×10^{-13}	6×10^{-6}	0.053	1.24×10^{-11}







Kink in ratio of the relic density is due to sudden jump in rates.



$$\frac{\Gamma^{BE}_{h\to\phi_D^*\phi_D}}{\Gamma^{MB}_{h\to\phi_D^*\phi_D}} = \frac{K_1(\frac{m_h}{T}) + 0.5K_1(\frac{2m_h}{T}) + 0.33K_1(\frac{3m_h}{T})..}{K_1(\frac{m_h}{T})}.$$

At EWSB, $m_h = 10$ *GeV*, $T_{EW} = 160$ *GeV*

$$\boxed{\frac{\Gamma^{BE}_{h\to\phi_D^*\phi_D}}{\Gamma^{MB}_{h\to\phi_D^*\phi_D}} = 1.472}$$

Conclusion

- Gauged $U(1)_{B-L}$ can simultaneously explain **neutrino mixing** and **dark matter**.

- The dark matter could be either **WIMP** or **FIMP** type in this model depending upon the choice of q_{DM}.

- Comparison between the relic density obtained by using BE/FD statistics, with the one obtained by using MB statistics
  - Annihilaton dominated scenarios (*1*,*2*) :- $\mathcal{R} = \frac{\Omega_{\rm BE} h^2}{\Omega_{\rm MB} h^2} \sim 1.42 - 1.62$
  - Decay dominated scenarios (*3*,*4*,*5*):- $\mathcal{R} = \frac{\Omega_{\rm BE} h^2}{\Omega_{\rm MB} h^2} < 1.04$

- Quantum statistics along thermal correction is necessary to capture enhancement effect in dark matter relic density in freeze-in scenarios


Thank
you