



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

Based on work with M.Mitra and P.Bandyopadhyay

[JHEP 05 (2021) 150]

Abhishek Roy

(Institute Of Physics, Bhubaneswar)

**ANOMALIES 2021**  
International Conference (online)  
IIT Hyderabad, Kandi, Telangana - 502285

**Contents**

- Gravitational wave like signature and finite temperature field theory
- Hadronic & leptonic colliders
- Flavour Physics & muon g-2
- Dark matter & Neutrino Physics

**National and International Organizing Committee**

- Dr. Priyotosh Bandyopadhyay  
Indian Institute of Technology, Hyderabad, India
- Prof. Rahul Sinha  
Institute of Mathematical Sciences, Chennai, India
- Dr. Bhupal Dev  
Washington University, St. Louis, US
- Prof. Amarjit Soti  
Brookhaven National Lab, Upton, US

**Local Organizers**

- Dr. Priyotosh Bandyopadhyay
- Prof. Anjan Chak
- Dr. Narenkra Sahu
- Dr. Rajbhavendra Srikanth Handi
- Dr. Saurabh Saandhya
- Dr. Anshuman Kishan

10th - 12th Nov, 2021

For registration, abstract submission, and other queries please visit the following website:  
<https://www.iitgh.ac.in/~anomalies19/anomalies2021.html>

Deadline for registration: 15th Oct, 2021  
Deadline for abstract submission: 5th Oct, 2021

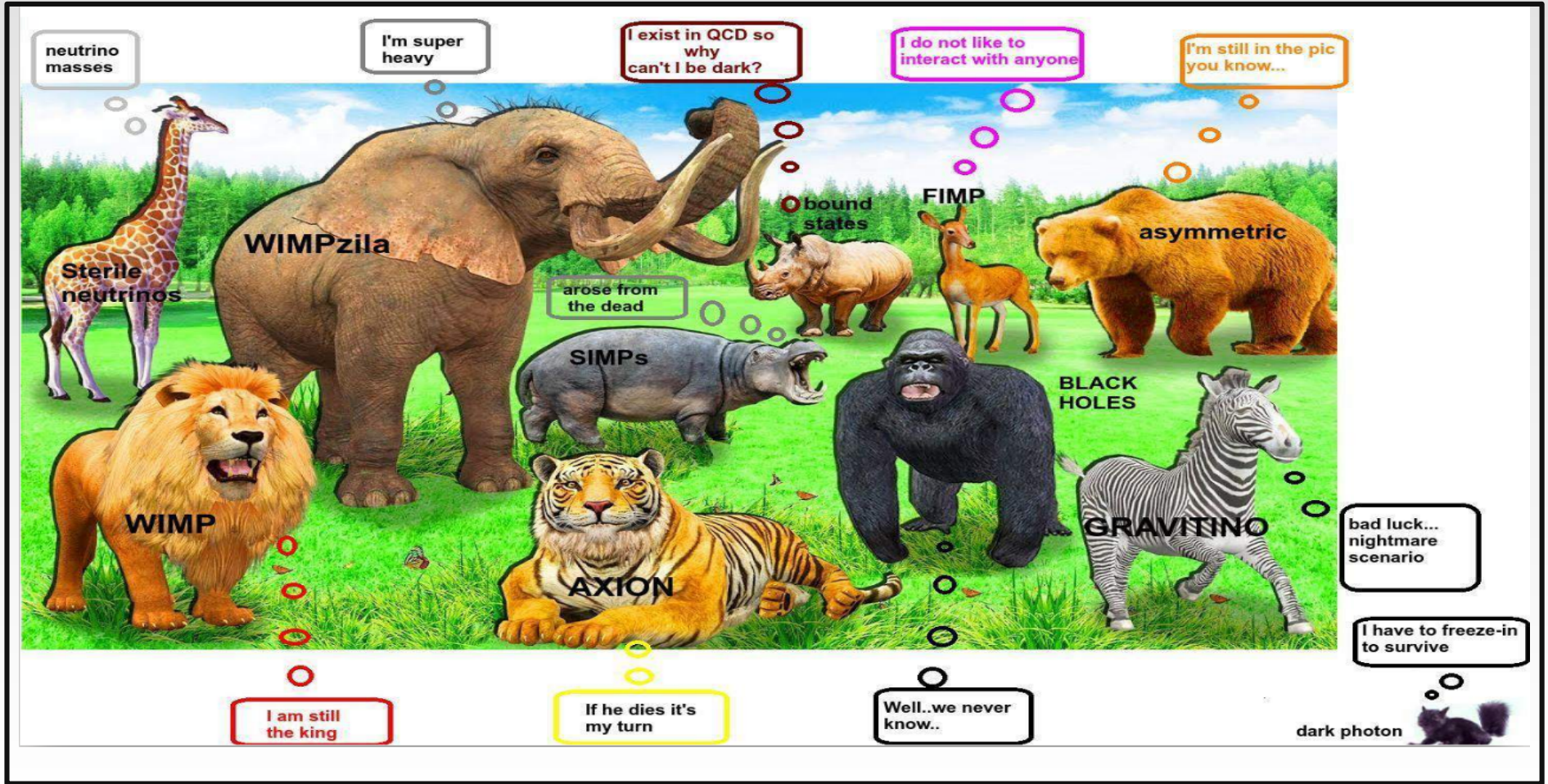
Logos for IIT Hyderabad, IOP, and Brookhaven National Laboratory are also present at the bottom.

# Talk Plan

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



# Zoo of Dark Matter Candidates



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

New Particles

Gauge Group	Baryon Fields			Lepton Fields			Scalar Fields		
	$Q_L^i = (u_L^i, d_L^i)^T$	$u_R^i$	$d_R^i$	$L_L^i = (\nu_L^i, e_L^i)^T$	$e_R^i$	$N_R^i$	$\Phi$	$\mathcal{S}$	$\phi_D$
$SU(2)_L$	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 parameter 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**

**B-L charge**

## Dark Matter(DM) Mass:-

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

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

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

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

$$q_{DM} \neq \pm 2n$$

$(n \in \mathbb{Z} \text{ and } n \leq 4)$

$\longrightarrow$   $\phi_D$  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,

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

$$V(\Phi, \mathcal{S}) = \mu_s^2 \mathcal{S}^\dagger \mathcal{S} + \mu_h^2 \Phi^\dagger \Phi + \lambda_s (\mathcal{S}^\dagger \mathcal{S})^2 + \lambda_h (\Phi^\dagger \Phi)^2 + \lambda_{sh} (\Phi^\dagger \Phi) (\mathcal{S}^\dagger \mathcal{S})$$

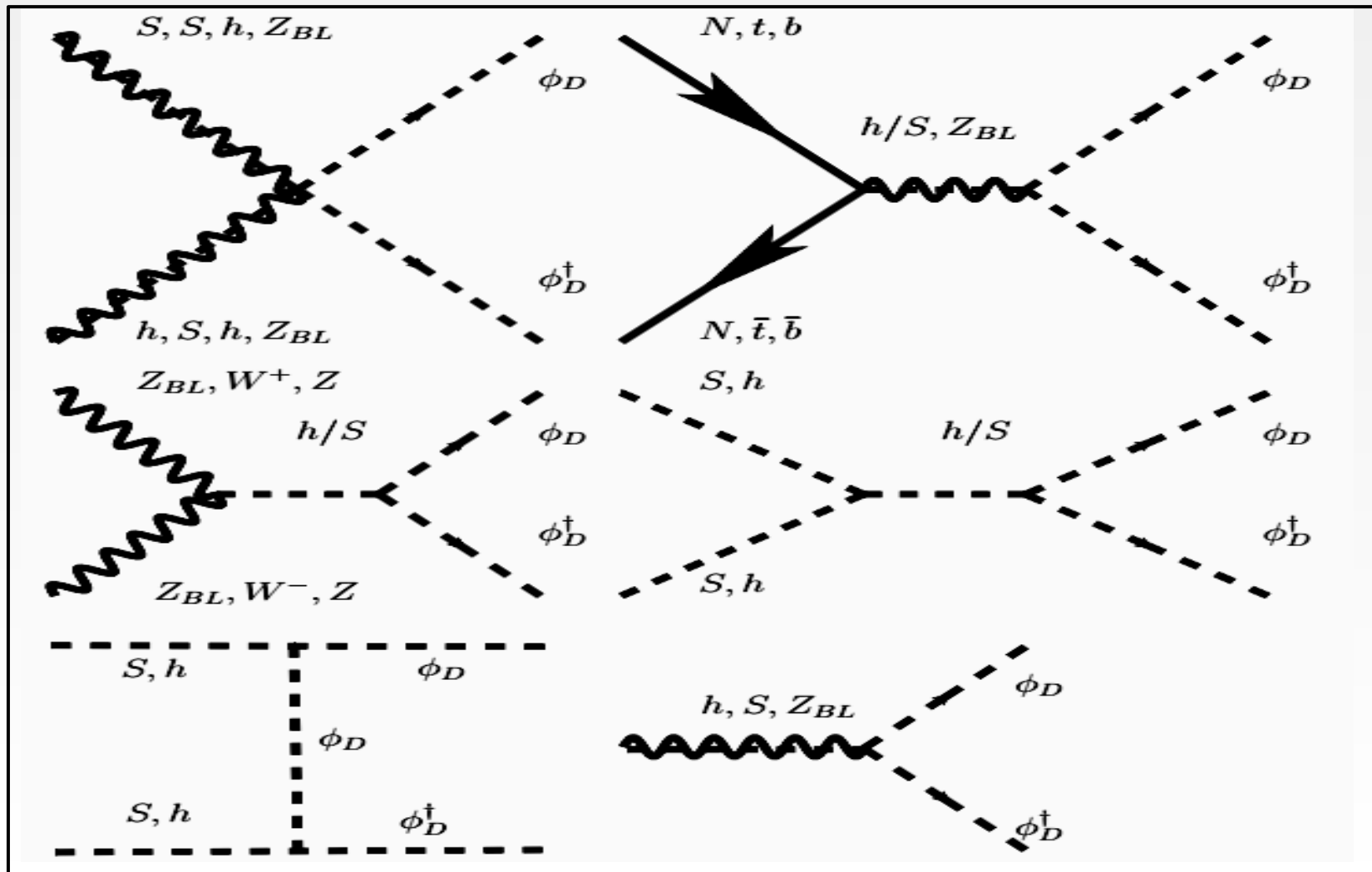
where

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

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

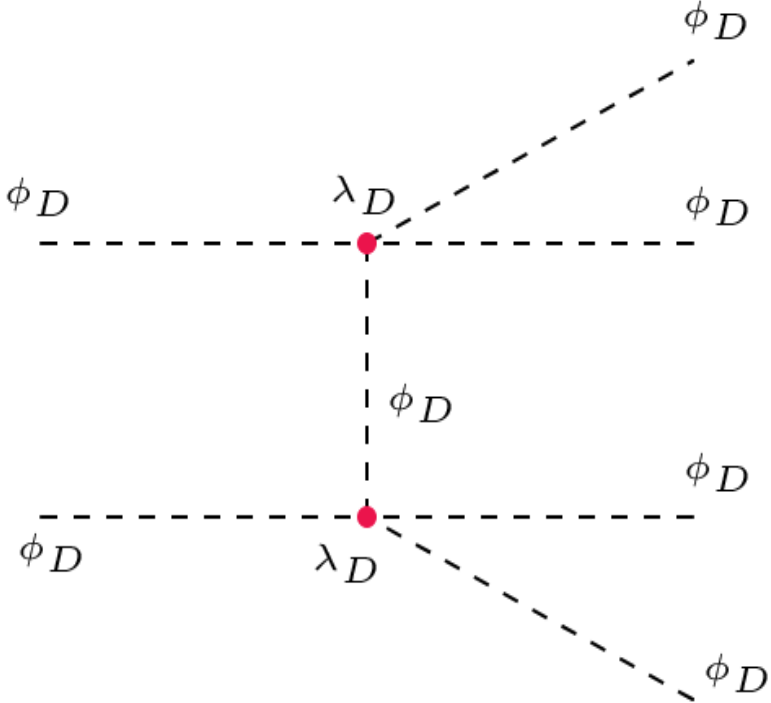
$g, g'$  are the SM gauge couplings and  $y_t$  is top-quark Yukawa coupling.

# Possible production modes of $\phi_D$

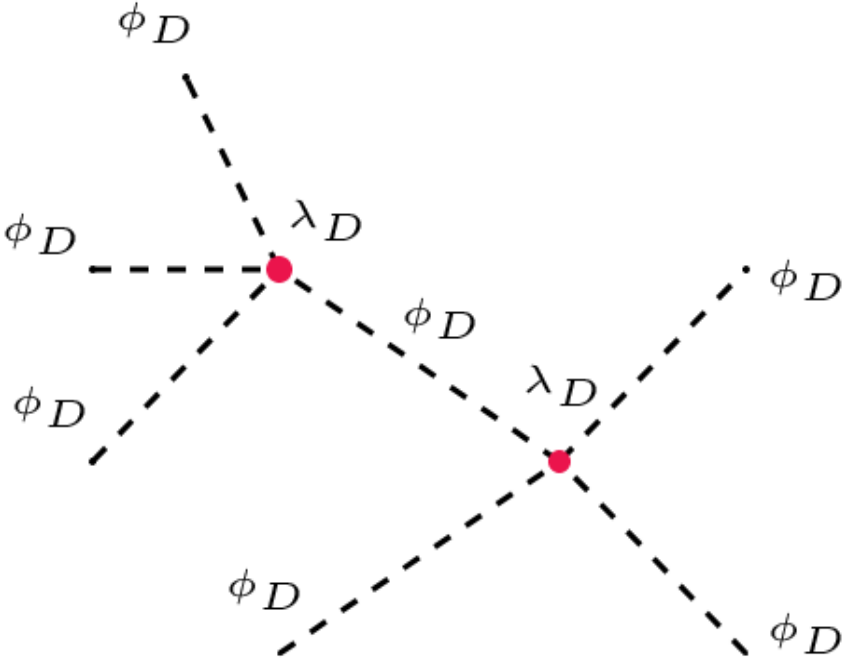




Possible production modes of  $\phi_D$



$2 \rightarrow 4$



$4 \rightarrow 2$

$\phi_D$  is gauged  $\longrightarrow$  thermalize  $\longrightarrow$  large  $g_{BL}$  coupling

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

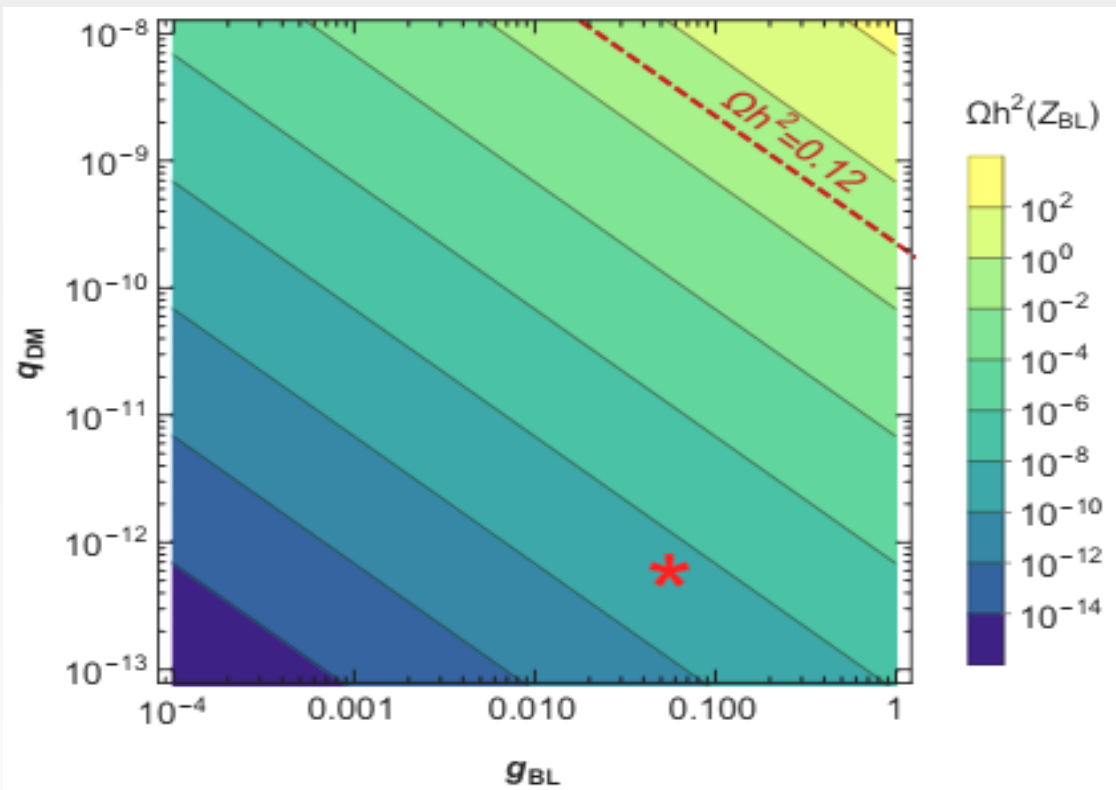
**To study relativistic freeze-in compels us to choose very small  $q_{DM}$ .**

The Boltzmann eqn. for the  $\phi_D$  via gauge interaction is,

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

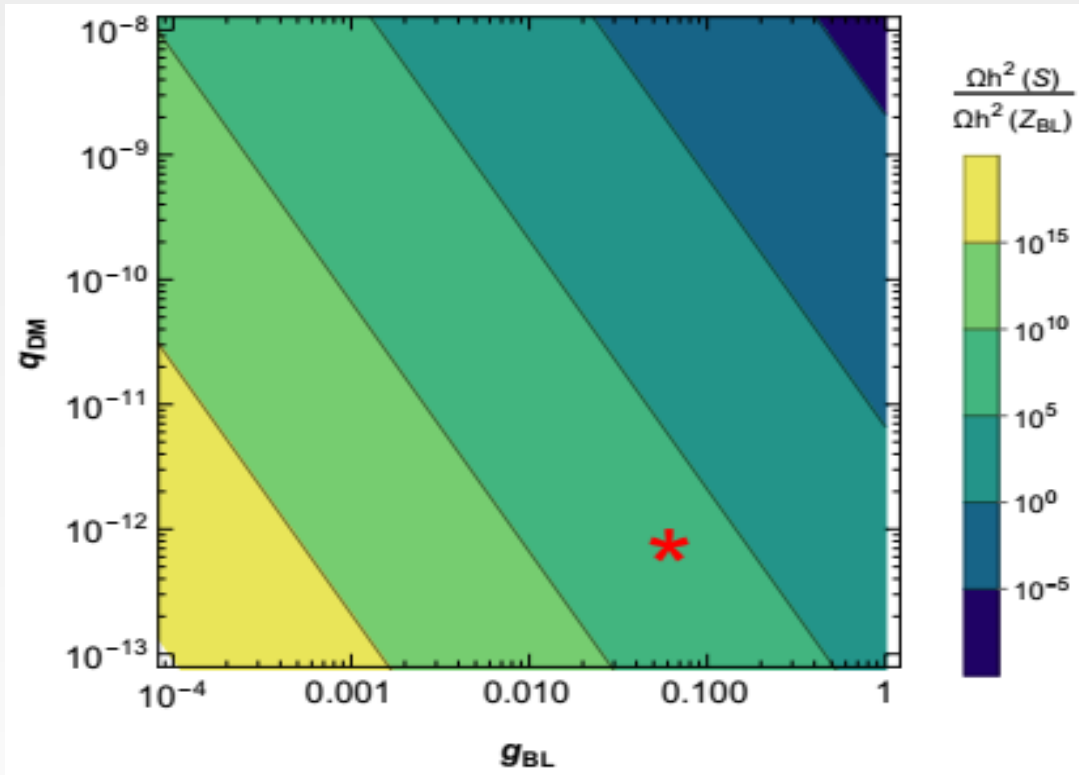
The relic abundance of  $\phi_D$  is given by,

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



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

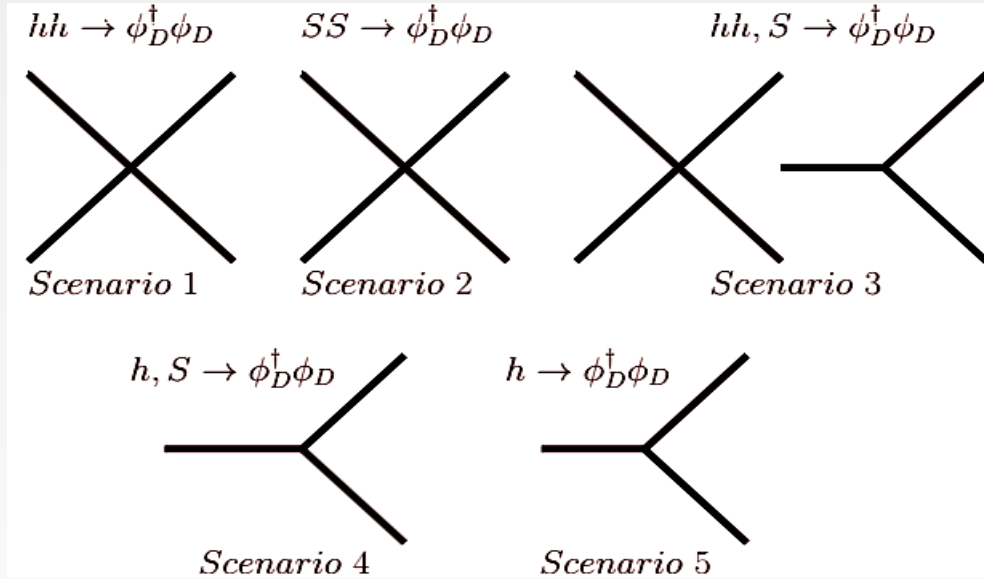
We choose  $q_{DM} \approx 10^{-12}$  represented by the red star in our analysis such production from gauge interaction is negligible.



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

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

# Different freeze-in scenarios depending on primary production mechanism.



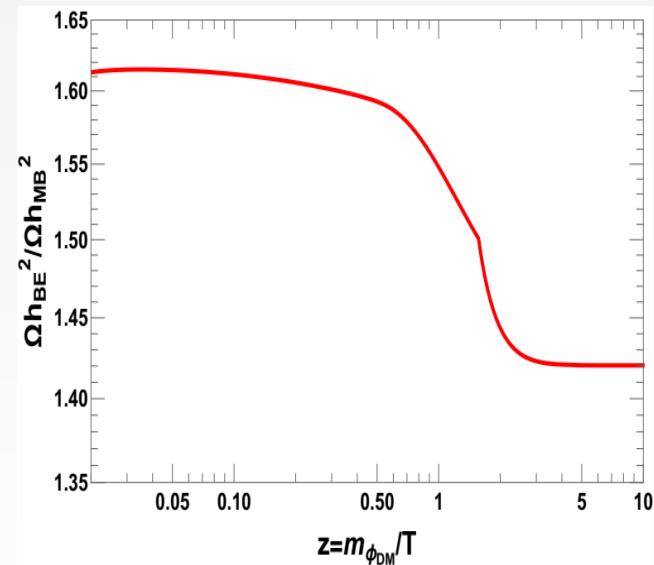
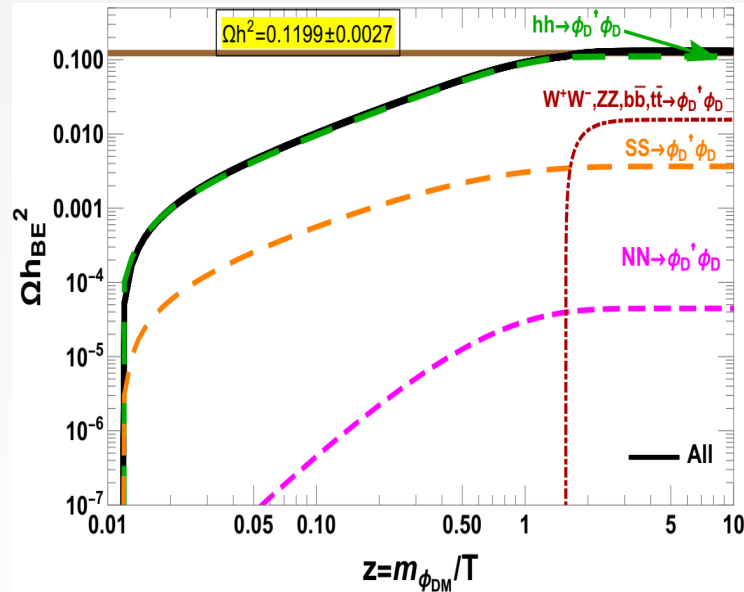
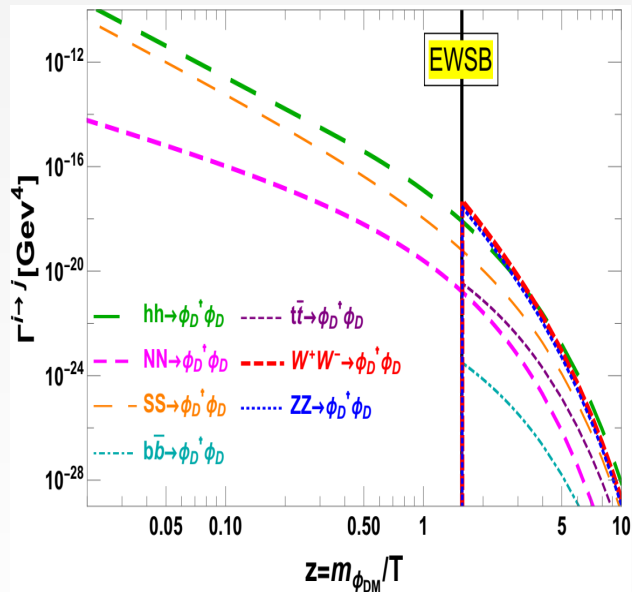
The Boltzmann equation is given by,

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

# Freeze-in Scenario 1:-

(SM Higgs boson annihilation dominant)

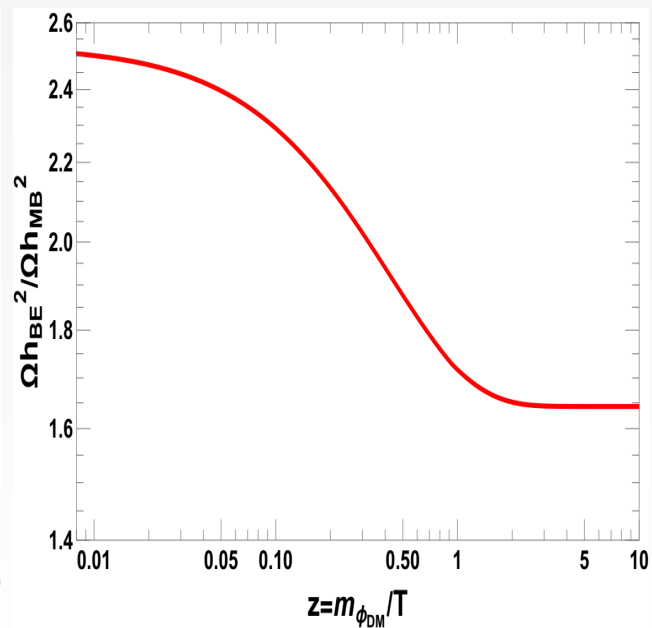
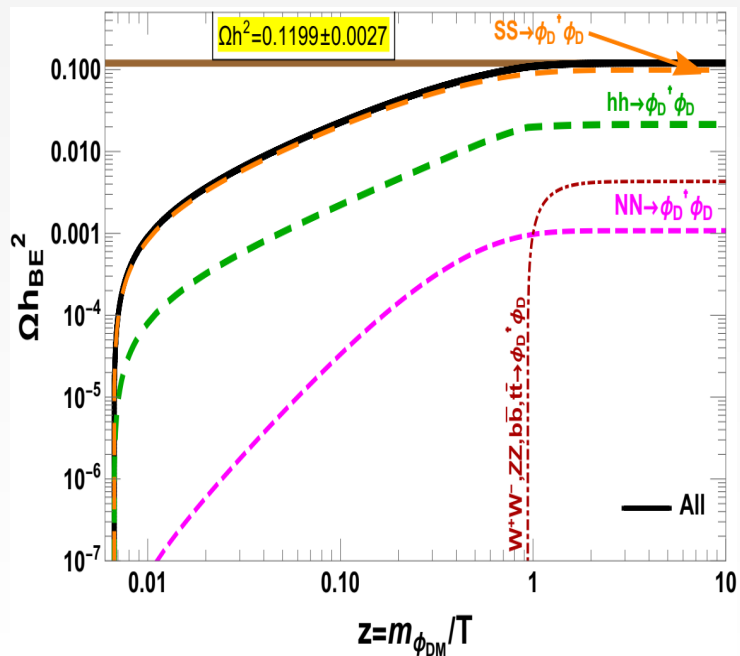
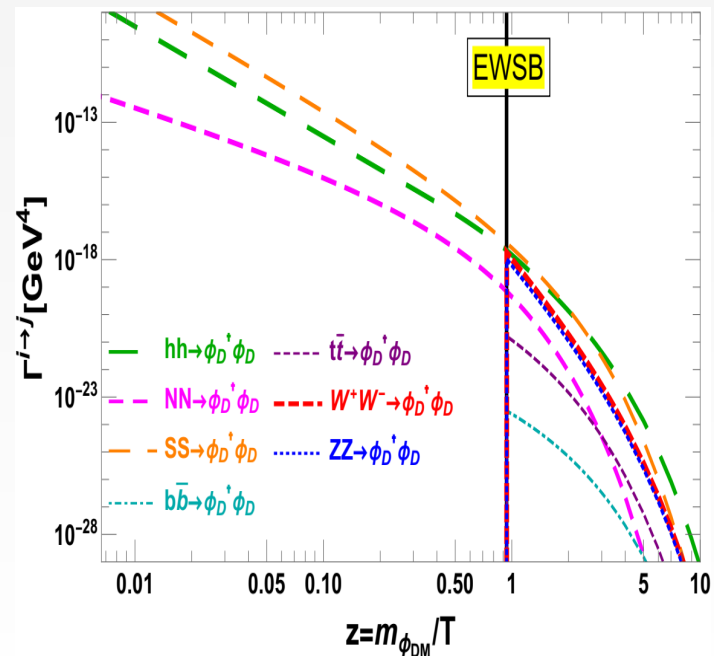
Scenario	Masses in GeV			Couplings				
	$m_S$	$m_N$	$m_{\phi_{DM}}$	$y_N$	$\lambda_{SD}$	$\lambda_{Sh}$	$\lambda_{NS}$	$\lambda_{Dh}$
1	200	300	250	$10^{-7}$	$5.0 \times 10^{-12}$	$6 \times 10^{-6}$	0.053	$1.6 \times 10^{-11}$



# Freeze-in Scenario 2:-

(BSM Higgs boson annihilation dominant)

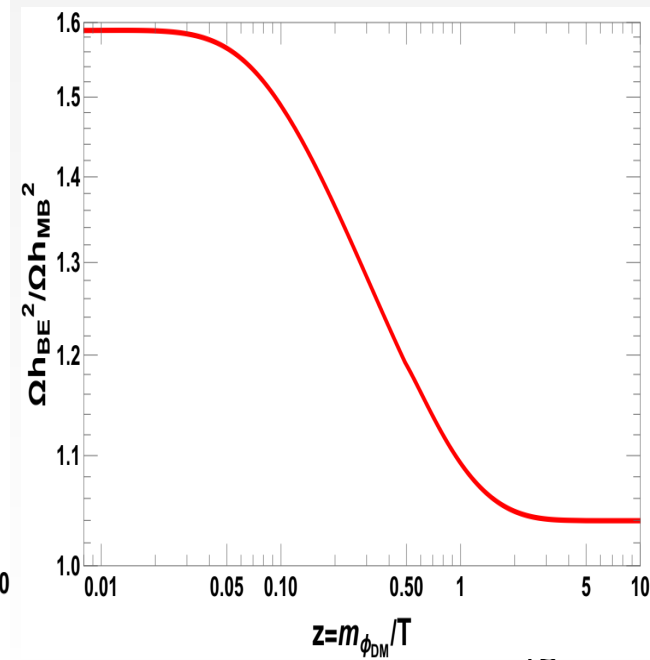
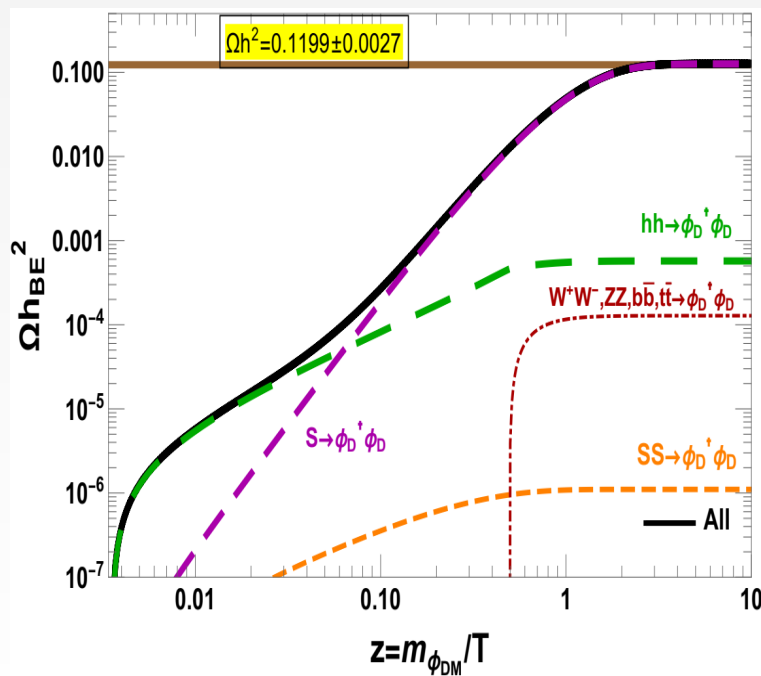
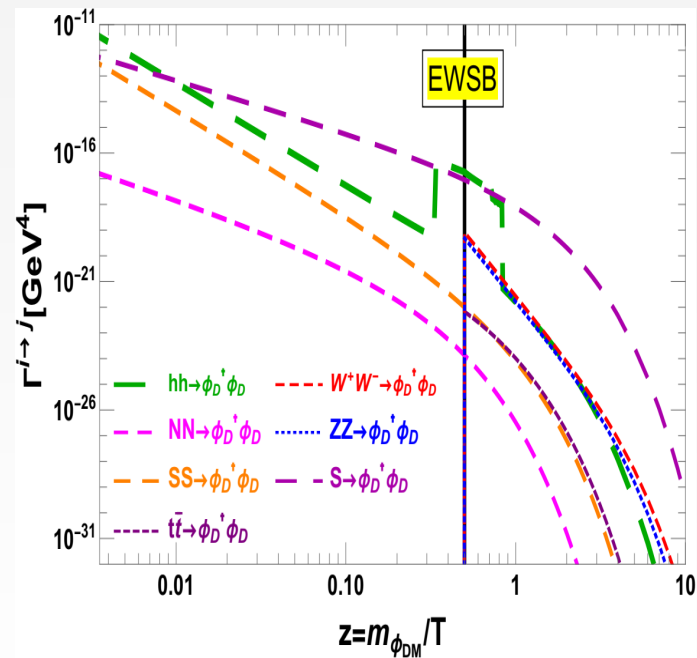
Scenario	Masses in GeV			Couplings				
	$m_S$	$m_N$	$m_{\phi_{DM}}$	$y_N$	$\lambda_{SD}$	$\lambda_{Sh}$	$\lambda_{NS}$	$\lambda_{Dh}$
2	200	300	150	$10^{-7}$	$3.0 \times 10^{-11}$	$6 \times 10^{-6}$	0.053	$7.5 \times 10^{-12}$



### Freeze-in Scenario 3:-

(BSM Higgs boson decay dominant)

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

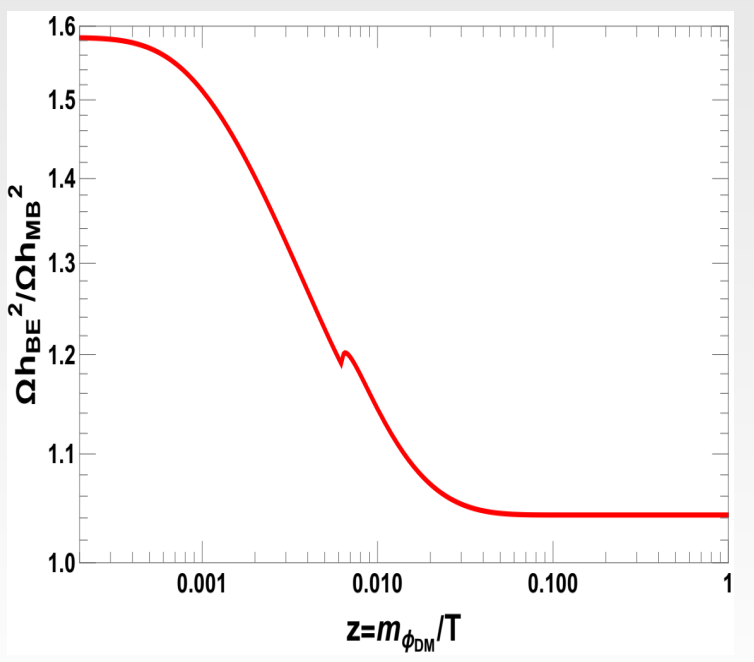
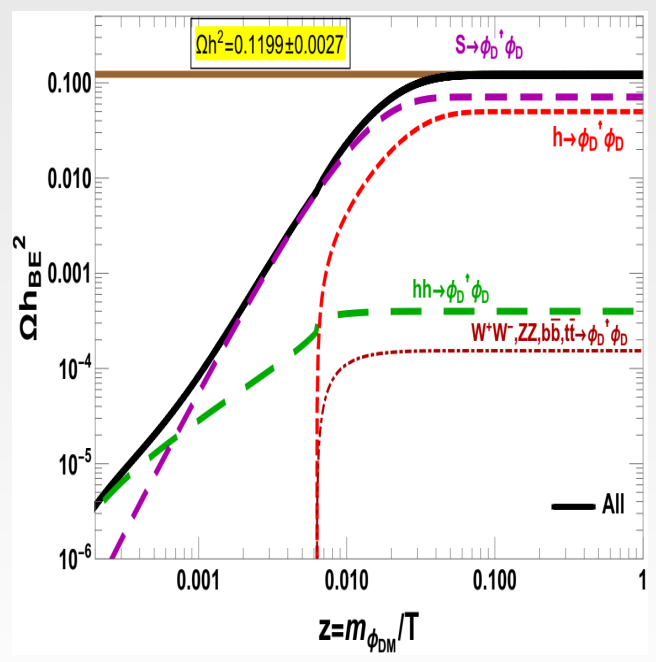
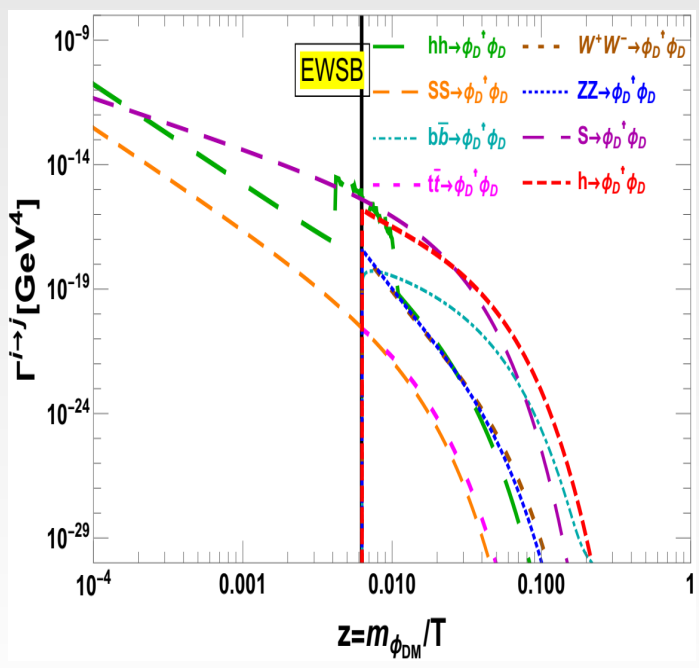




# Freeze-in Scenario 4:-

## (BSM Higgs boson decay dominant)

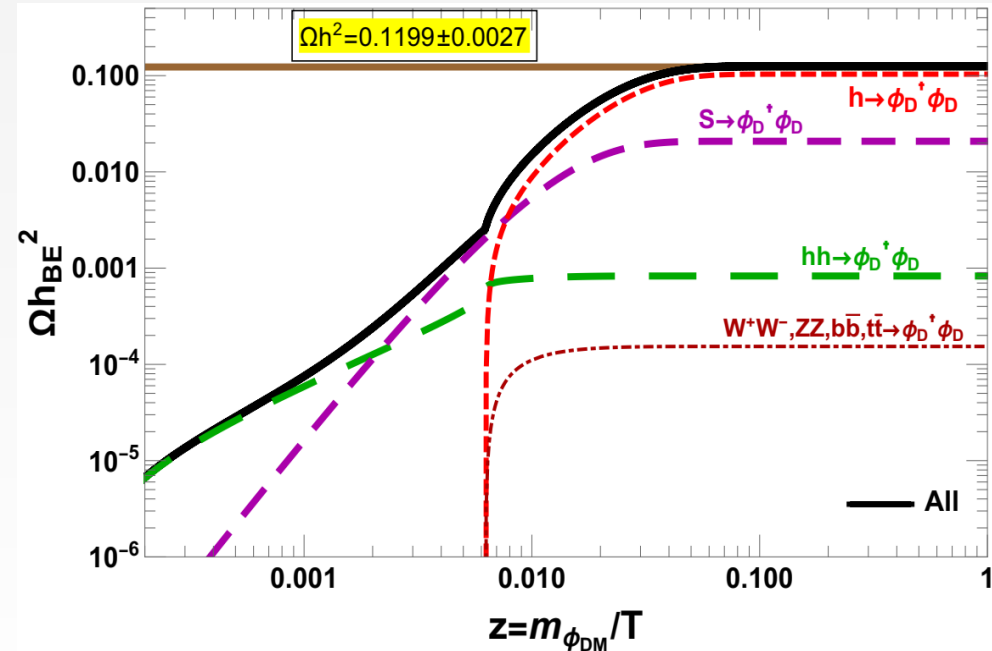
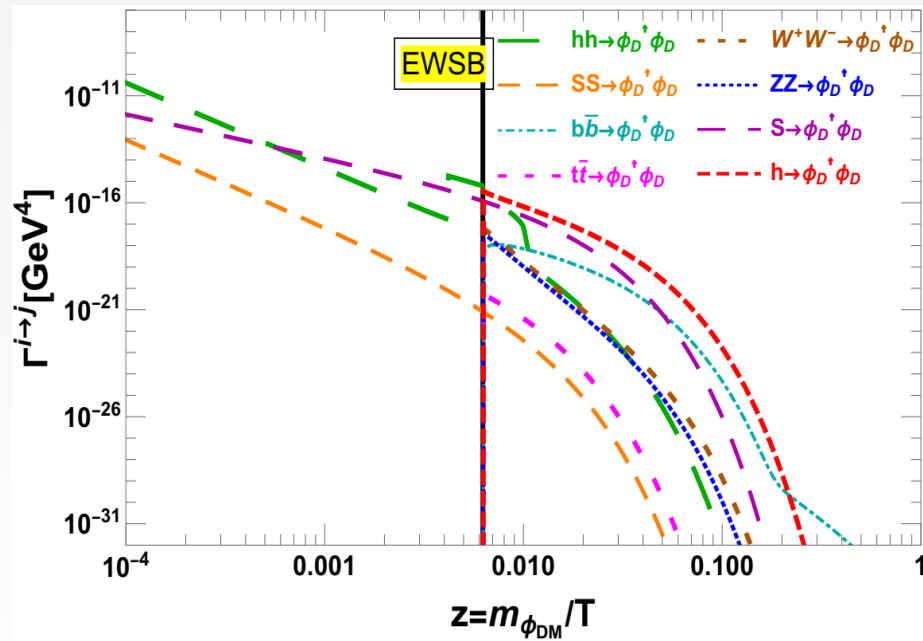
Scenario	Masses in GeV			Couplings				
	$m_S$	$m_N$	$m_{\phi_{DM}}$	$y_N$	$\lambda_{SD}$	$\lambda_{Sh}$	$\lambda_{NS}$	$\lambda_{Dh}$
4	200	300	1	$10^{-7}$	$6.65 \times 10^{-13}$	$6 \times 10^{-6}$	0.053	$8.6 \times 10^{-12}$

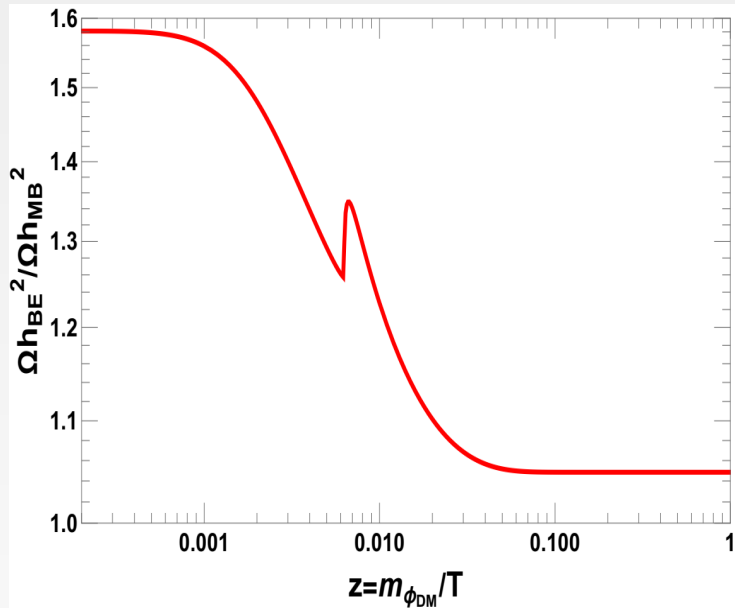


## Freeze-in Scenario 5:-

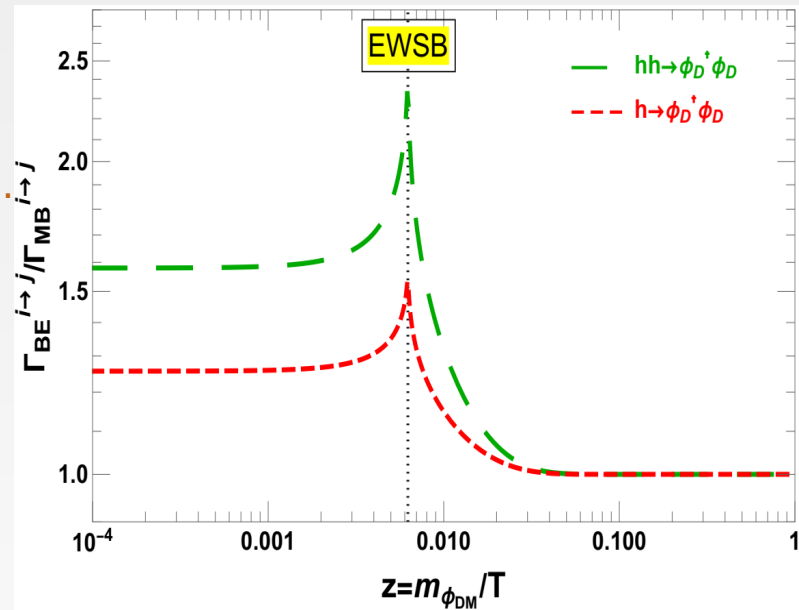
(SM Higgs boson decay dominant)

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





Kink due to sudden jump in rates.



$$\frac{\Gamma_{h \to \phi_D^* \phi_D}^{BE}}{\Gamma_{h \to \phi_D^* \phi_D}^{MB}} = \frac{K_1\left(\frac{m_h}{T}\right) + 0.5K_1\left(\frac{2m_h}{T}\right) + 0.33K_1\left(\frac{3m_h}{T}\right) \dots}{K_1\left(\frac{m_h}{T}\right)}$$

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

$$\frac{\Gamma_{h \to \phi_D^* \phi_D}^{BE}}{\Gamma_{h \to \phi_D^* \phi_D}^{MB}} = 1.472$$

# 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) :-  $\mathcal{R} = \frac{\Omega_{BE}h^2}{\Omega_{MB}h^2} \sim 1.42 - 1.62$
  - Decay dominated scenarios (3,4,5):-  $\mathcal{R} = \frac{\Omega_{BE}h^2}{\Omega_{MB}h^2} < 1.04$
- Quantum statistics along thermal correction is necessary to capture enhancement effect in dark matter relic density in freeze-in scenarios

Thank  
you

