Viability of Boosted Light Dark Matter in a Two-Component Scenario

Arindam Basu

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Reference:
"Viability of Boosted Light Dark Matter in a Two-Component Scenario" , A Basu , A Chakraborty, N. Kumar, and S. Sadhukhan (https://arxiv.org/abs/2310.09349)

Motivation:

- The existence of Dark Matter (DM) is proven only through indirect gravitational probes.
- Astrophysical observation predicts the amount of DM ($\sim$ 26.8 %) of the total energy of the Universe.
- A Plethora of DM direct and indirect detections for WIMP are only of minimal success.
- We are studying **light DM (MeV-GeV scale)**.
- The light DM can receive sufficient energy for the nuclear recoil if it is boosted.
- Detection prospects get better with the boost.

Model Description:

Neutrinophilic Two Higgs doublet model **ν2HDM**. Φ_1 and Φ_2

Neutrinophilic suggests a strong coupling between one doublet and N_R.

+

Yukawa interaction of the model

$$\mathcal{L}_Y = Y^d_{\alpha\beta}\bar{Q}_{L,\alpha}\Phi_1 d_{R,\beta} + Y^u_{\alpha\beta}\bar{Q}_{L,\alpha}\tilde{\Phi}_1 u_{R,\beta} + Y^l_{\alpha\beta}\bar{L}_{L,\alpha}\Phi_1 l_{R,\beta} + Y^\nu_{\alpha\beta}\bar{L}_{L,\alpha}\tilde{\Phi}_2 N_{R,\beta} + \text{h.c.}$$

N_R is the RHN. Odd under Z_2.

+

Scalar singlet ϕ_3 gives MeV scale scalar DM

$$V_{DM} = \frac{1}{2}m^2_{\phi_3}\phi_3^2 + \frac{\lambda_{\phi_3}}{4!}\phi_3^4 + \kappa_1\Phi_1^\dagger\Phi_1\phi_3^2 + \kappa_2\Phi_2^\dagger\Phi_2\phi_3^2.$$

+

Vector-like doublet **N**
Vector-like singlet χ

$$L_{VLL} = m_N\bar{N}N + m_\chi\bar{\chi}\chi + y_N\bar{N}\tilde{\Phi}_1\chi + h.c.$$

arxiv: 0711.4022
0802.4353
1011.6188

Model Description: Fields & Charge Assignments:

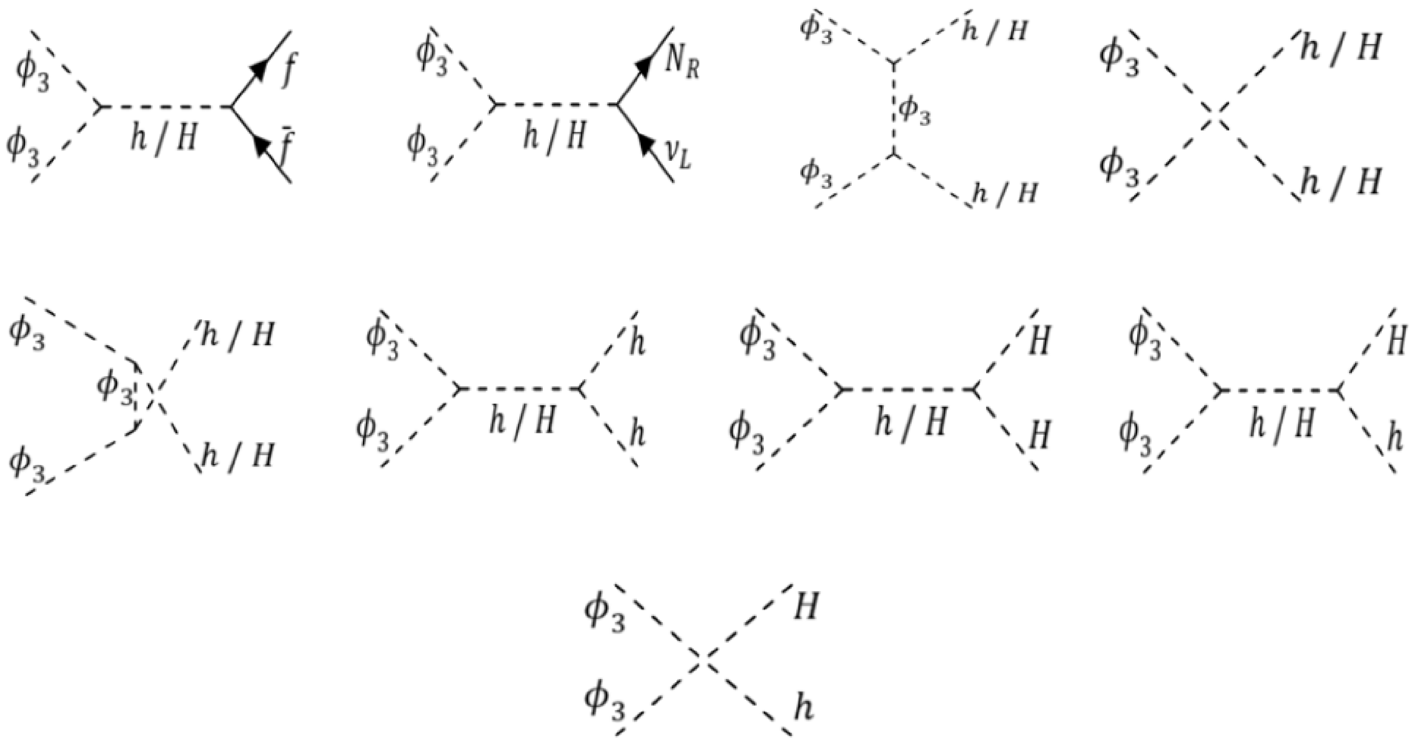
Particle Name	$SU(2)_L$ Charges	$U(1)_Y$ Charges	Z_2 Charges	$Z_2^{\rm DM}$ Charges
Scalar Fields				
Φ_1	2	1	1	1
Φ_2	2	1	-1	1
ϕ_3	1	0	1	-1
Fermionic Fields				
N	2	-1	1	-1
χ	1	0	1	-1

- Φ_3 is the scalar MeV scale DM.
- Mixing of ***N*** and χ produces the heavy fermionic DM χ_1. $m_{\chi 1} \sim 100$ *GeV*.
- Φ_2 is even under Z_2^{DM}-> suggests that it provides a portal interaction and does not serve as a DM candidate.
- Odd under Z_2^{DM}-> suggests stable DM candidate.

Dark Matter: Relic Density Aspects: MeV scale Scalar Singlet DM:

Feynman Diagrams for the scalar DM annihilation

Scalar DM ϕ_3:



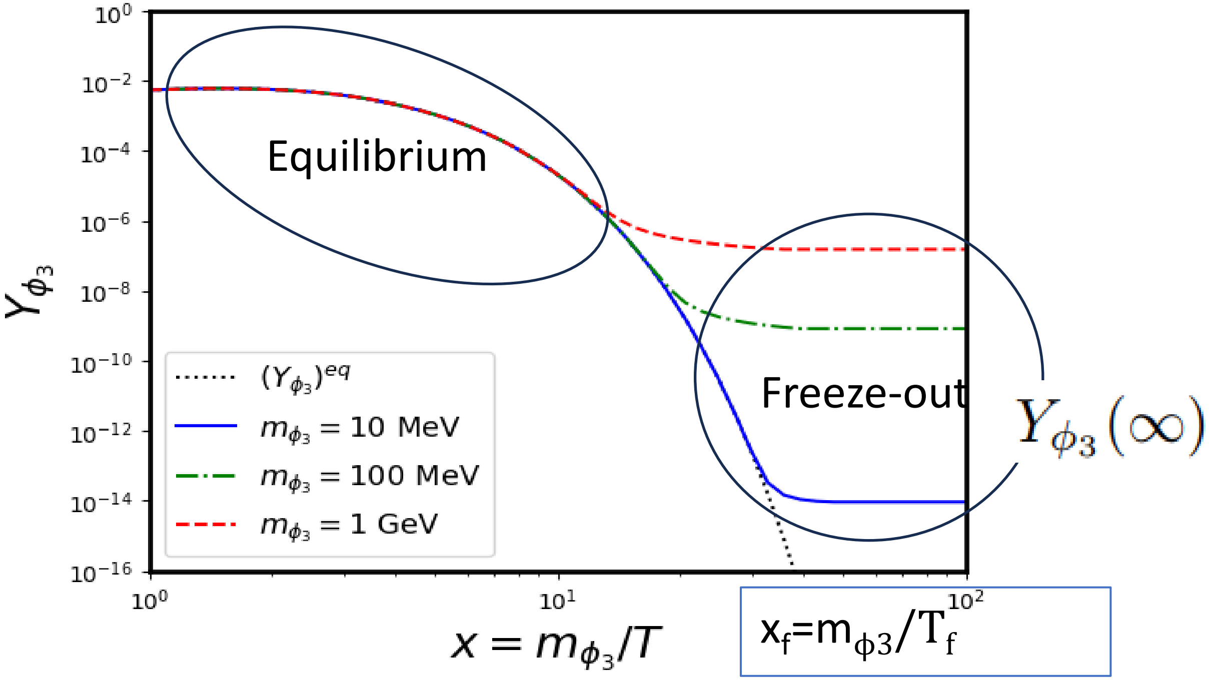
$$\sigma_{\phi_3} = \sigma(s)_{\phi_3\phi_3 \to f\bar{f}} + \sigma(s)_{\phi_3\phi_3 \to N_R \nu_L} + \sigma(s)_{\phi_3\phi_3 \to HH} + \sigma(s)_{\phi_3\phi_3 \to hh} + \sigma(s)_{\phi_3\phi_3 \to hH}$$

Dark Matter: Relic Density Aspects: Scalar Singlet DM:

$$\frac{dY_{\phi_3}}{dx} = -\frac{1}{x^2}\frac{s(m_{\phi_3})}{H(m_{\phi_3})}\langle\sigma v\rangle_{\phi_3\phi_3\to SM}(Y_{\phi_3}^2 - Y_{\phi_3,\mathrm{eq}}^2)$$

$$Y_{\phi_3,eq} = 0.145\frac{g_i}{g*}x^{3/2}e^{-x}$$

$$\Omega_{\phi_3}h^2 = \frac{m_{\phi_3}\ s_0\ Y_{\phi_3}(\infty)}{\rho_c/h^2}$$



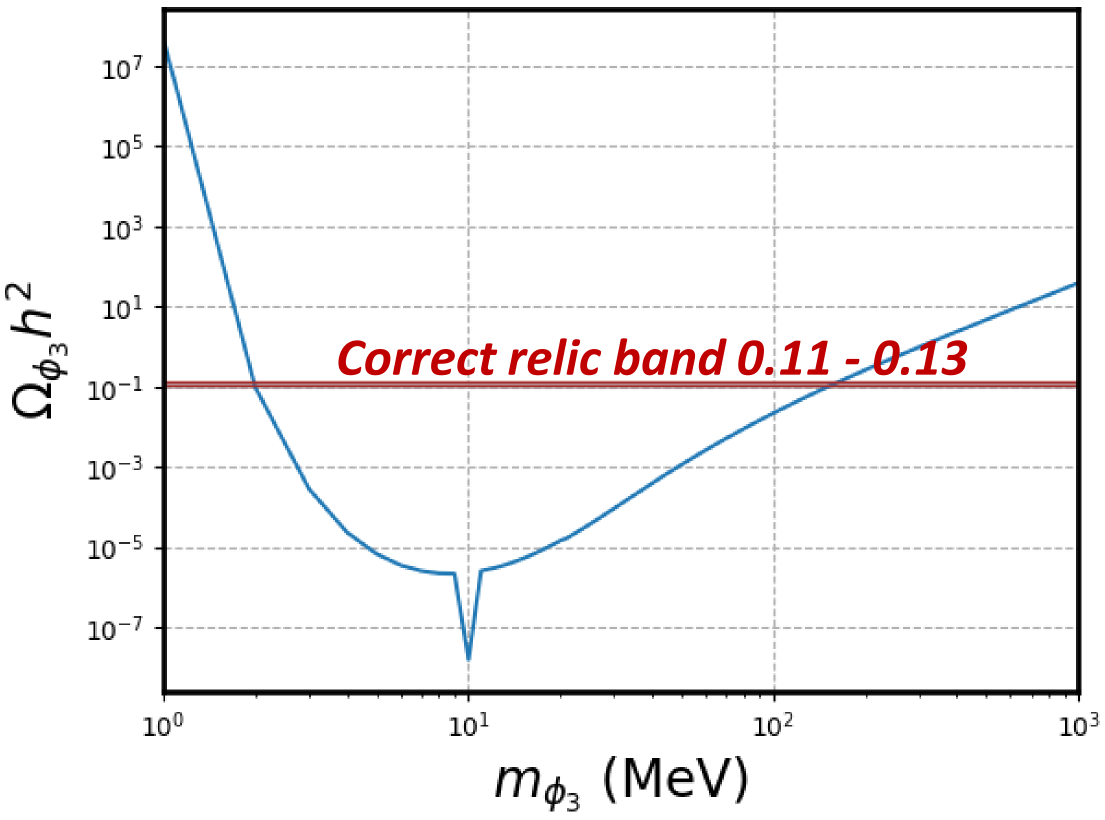
Scalar DM	
Mass	Relic density
10 MeV	2.43×10^{-8}
100 MeV	2.10×10^{-2}
1 GeV	36.9

Dark Matter: Relic Density Aspects: Scalar Singlet DM:

$$\Omega h^2 = \frac{2.14 \times 10^9 \ \mathrm{GeV}^{-1}}{\sqrt{g_*}\ M_{pl}} \frac{1}{J(x_f)}$$

$$J(x_f) = \int_{x_f}^{\infty} \frac{\langle \sigma v \rangle (x)}{x^2} \, dx$$

<σv> is the thermal averaged cross-section



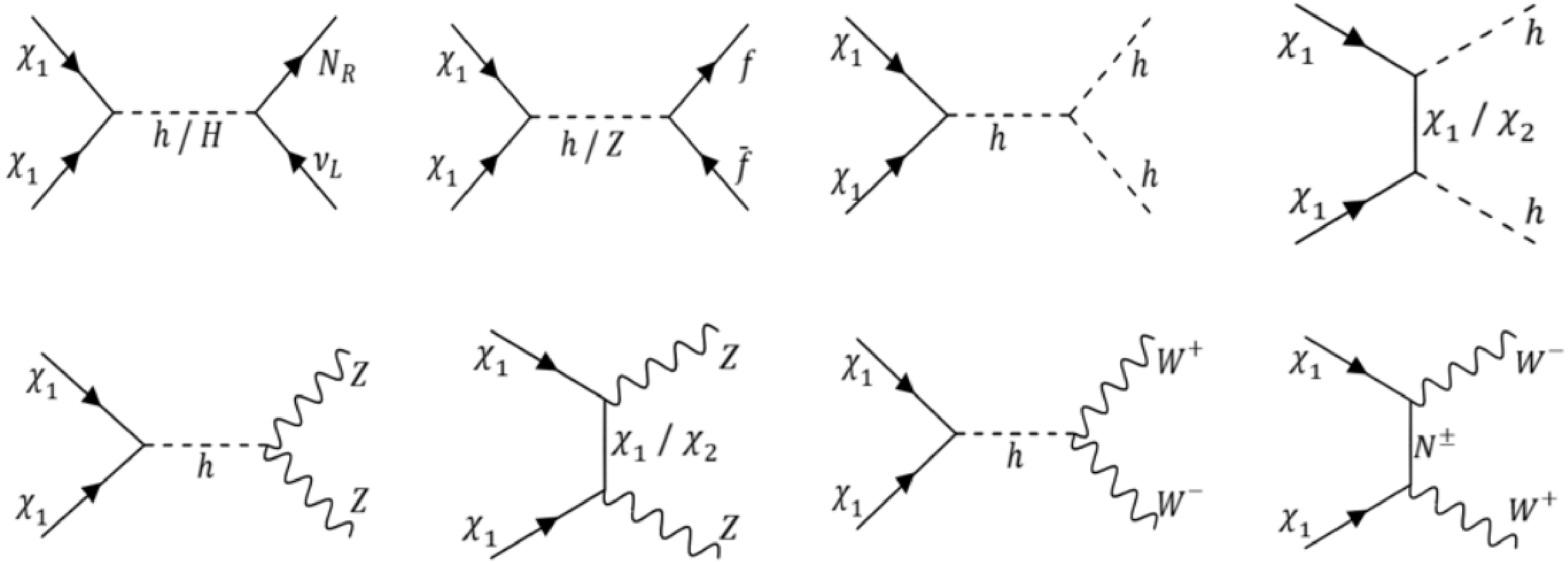
Allowed window 2-120 MeV

References: https://arxiv.org/pdf/0804.2741
https://arxiv.org/pdf/2006.09721
https://arxiv.org/pdf/1808.01272

Dark Matter: Relic Density Aspects: Fermionic DM:

Feynman Diagrams for the fermionic DM annihilation

Fermionic DM χ_1:



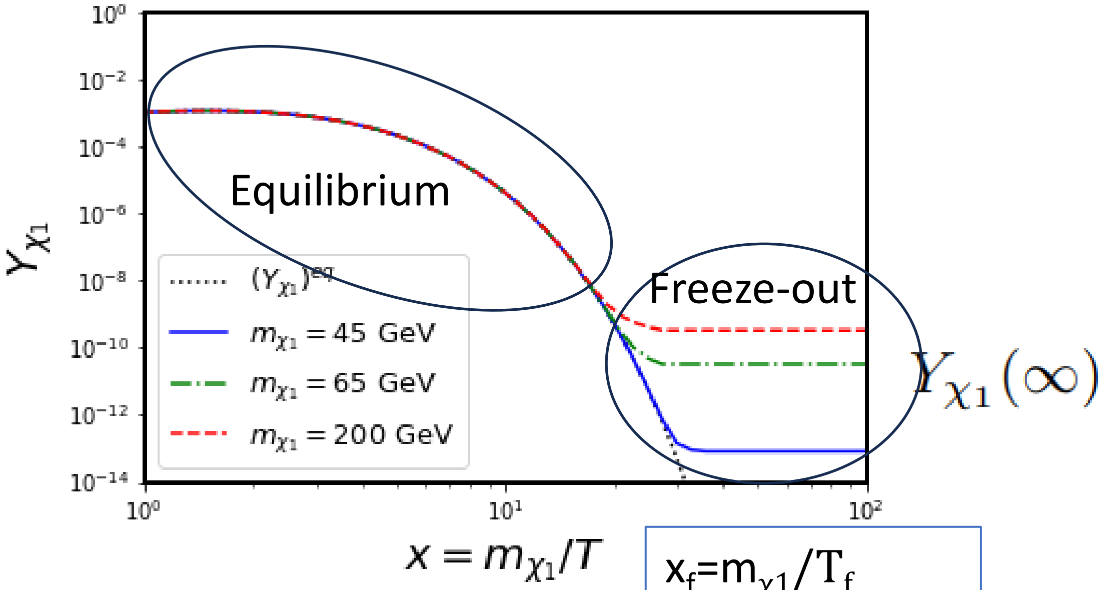
$$\sigma_{\chi_1} = \sigma(s)_{\chi_1\chi_1\to f\bar{f}} + \sigma(s)_{\chi_1\chi_1\to N_R\nu_L} + \sigma(s)_{\chi_1\chi_1\to hh} + \sigma(s)_{\chi_1\chi_1\to ZZ} + \sigma(s)_{\chi_1\chi_1\to W^+W^-}$$

Dark Matter: Relic Density Aspects: Fermionic DM:

$$\frac{dY_{\chi_1}}{dx} = -\frac{1}{2}\frac{1}{x^2}\frac{s(m_{\chi_1})}{H(m_{\chi_1})}\langle\sigma v\rangle_{\chi_1\chi_1\to SM}(Y^2_{\chi_1} - Y^2_{\chi_1,\mathrm{eq}})$$

$$Y_{\chi_1,eq} = 0.145\frac{g_i}{g*}x^{3/2}e^{-x}$$

$$\Omega_{\chi_1}h^2 = \frac{m_{\chi_1}\ s_0\ Y_{\chi_1}(\infty)}{\rho_c/h^2}$$

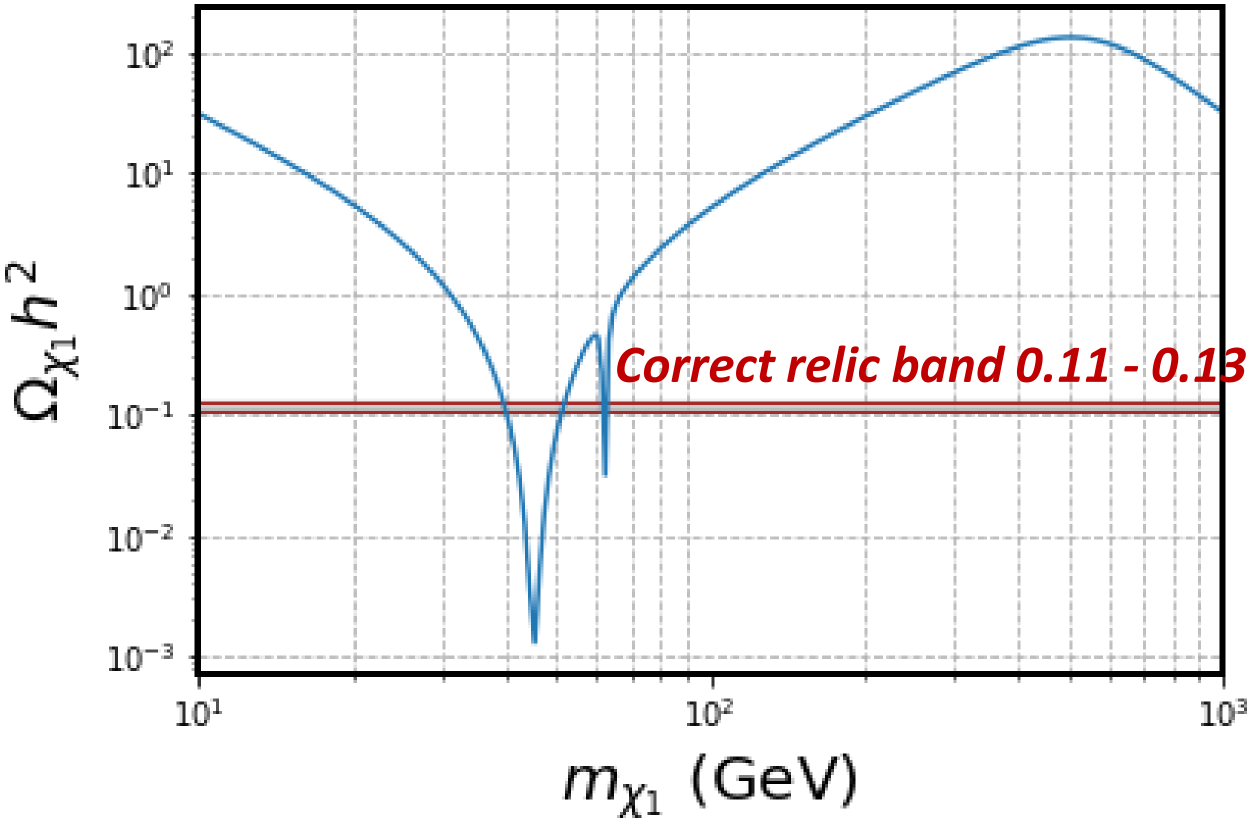


$x_f = m_{\chi 1}/T_f$

Fermion DM	
Mass	Relic density
45 GeV	2.07×10^{-3}
65 GeV	0.67
200 GeV	22.16

Dark Matter: Relic Density Aspects: Fermionic DM:

$$\Omega_{\chi_1} h^2 = \frac{2.14 \times 10^9 \, x_f}{\sqrt{g^*} M_{pl} \langle \sigma v \rangle}$$

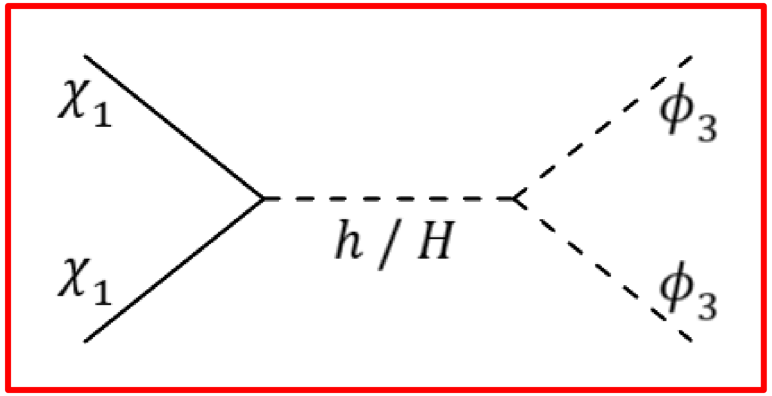


References: https://arxiv.org/pdf/1812.06505
https://arxiv.org/pdf/1510.02760

Allowed window 40 GeV – 50 GeV.

Two-component DM: Coupled Boltzmann Equation :

Higgs portal interaction between the two DM candidates serves as the connector between the two DM candidate

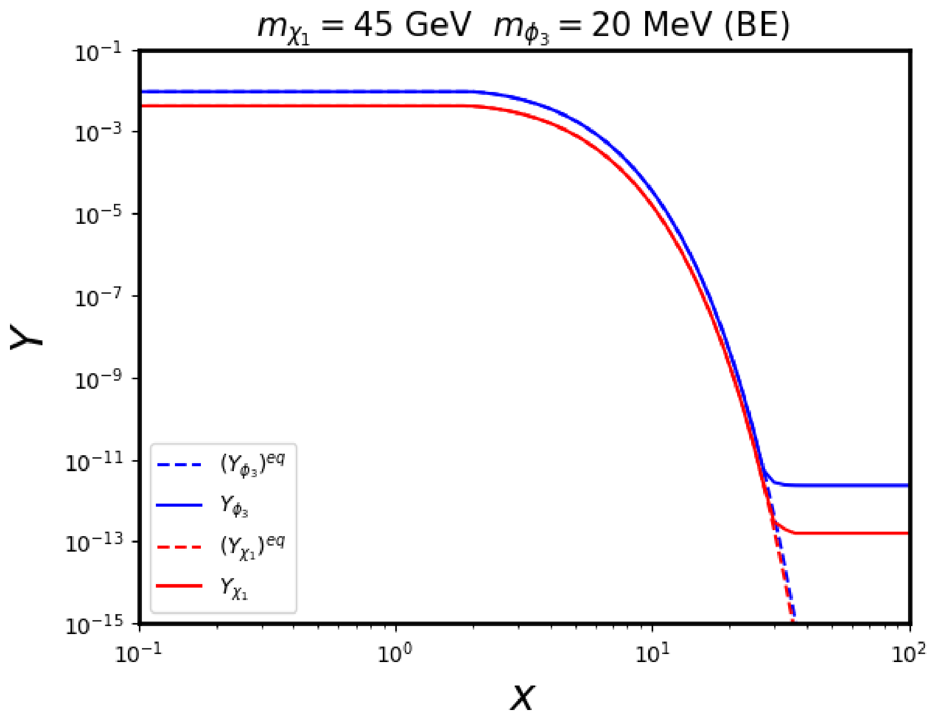


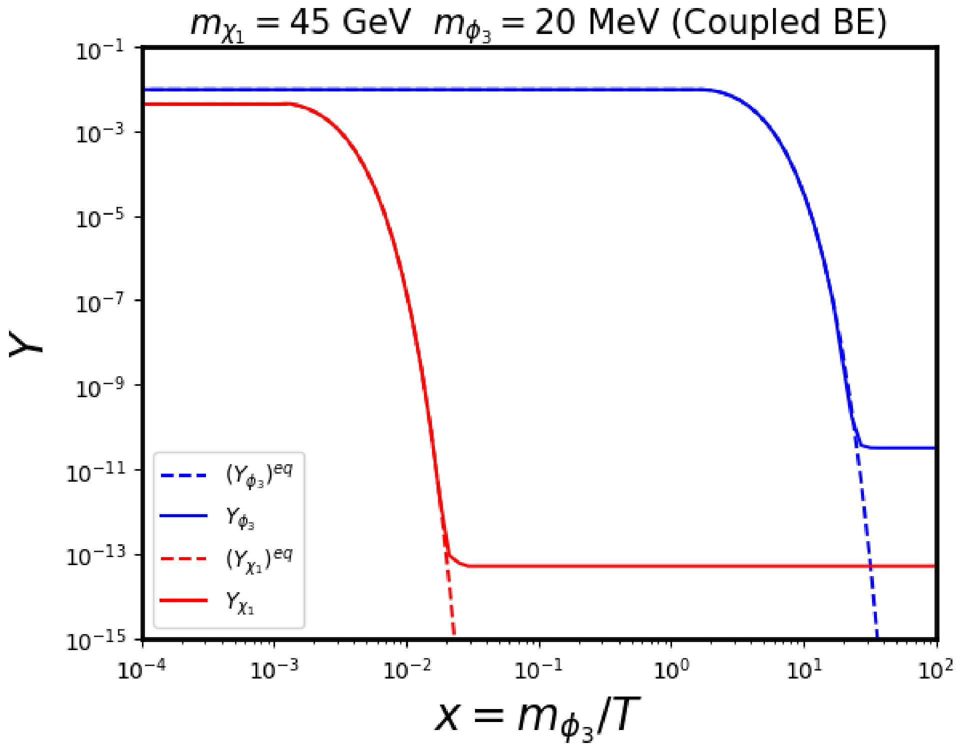
$$\frac{dY_{\chi_1}}{dx} = -\frac{1}{2}\frac{\lambda_{\chi\phi}}{x^2}\left(Y_{\chi_1}^2 - Y_{\phi_3}^2\frac{Y_{\chi_1,\mathrm{eq}}^2}{Y_{\phi_3,\mathrm{eq}}^2}\right) - \frac{1}{2}\frac{\lambda_\chi}{x^2}\left(Y_{\chi_1}^2 - Y_{\chi_1,\mathrm{eq}}^2\right)$$

$$\frac{dY_{\phi_3}}{dx} = -\frac{\lambda_\phi}{x^2}\left(Y_{\phi_3}^2 - Y_{\phi_3,\mathrm{eq}}^2\right) + \frac{\lambda_{\chi\phi}}{x^2}\left(Y_{\chi_1}^2 - Y_{\phi_3}^2\frac{Y_{\chi_1,\mathrm{eq}}^2}{Y_{\phi_3,\mathrm{eq}}^2}\right)$$

Two-component DM: Coupled Boltzmann Equation :

$m_{\chi 1}$ = **45 GeV** $m_{\phi 3}$ = **20 MeV**





$\Omega_{\chi_1} h^2 =$ **2.07 * 10^-3^**

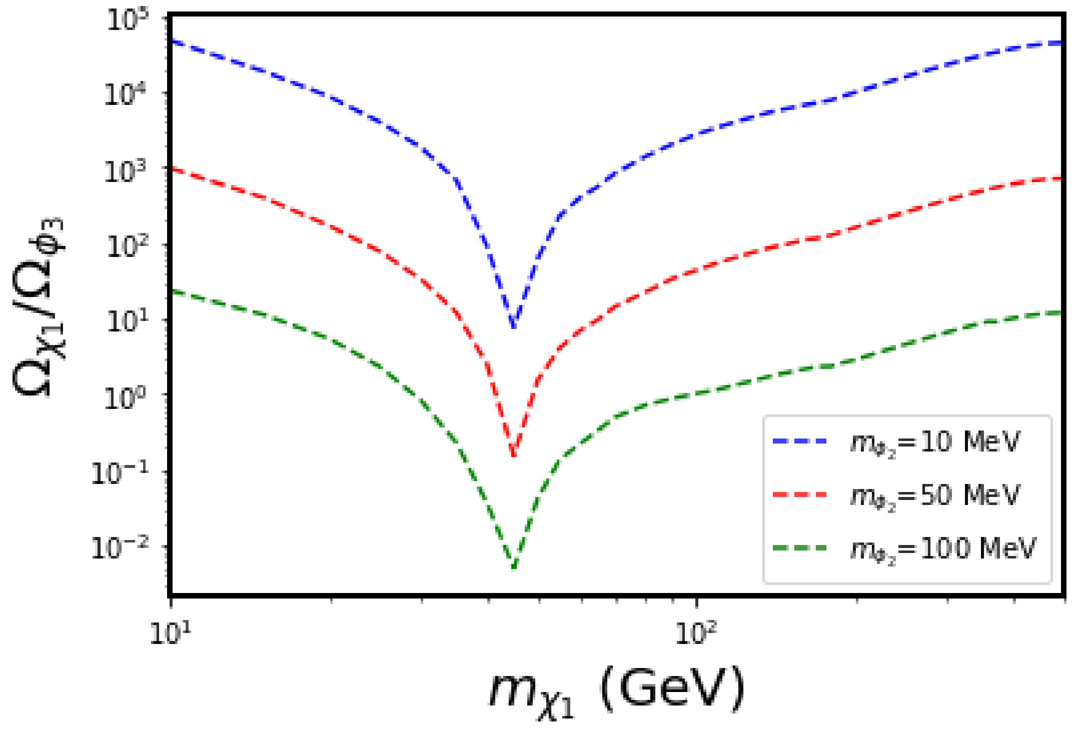
$\Omega_{\phi_3} h^2 =$ **5.50 * 10^-6^**

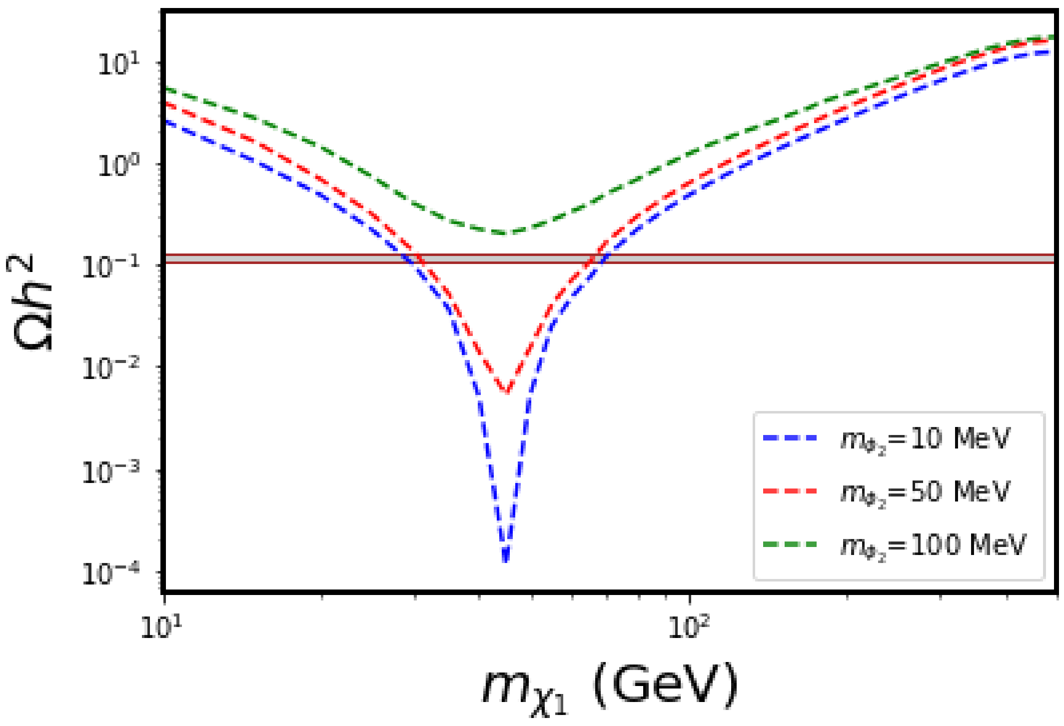
$\Omega_{\chi_1} h^2 =$ **6.2 * 10^-4^**

$\Omega_{\phi_3} h^2 =$ **1.2 * 10^-4^**

$\Omega h^2 = \Omega_{\chi_1} h^2 + \Omega_{\phi_3} h^2 =$ **7.4 * 10^-4^**

Two-component DM: Coupled Boltzmann Equation :

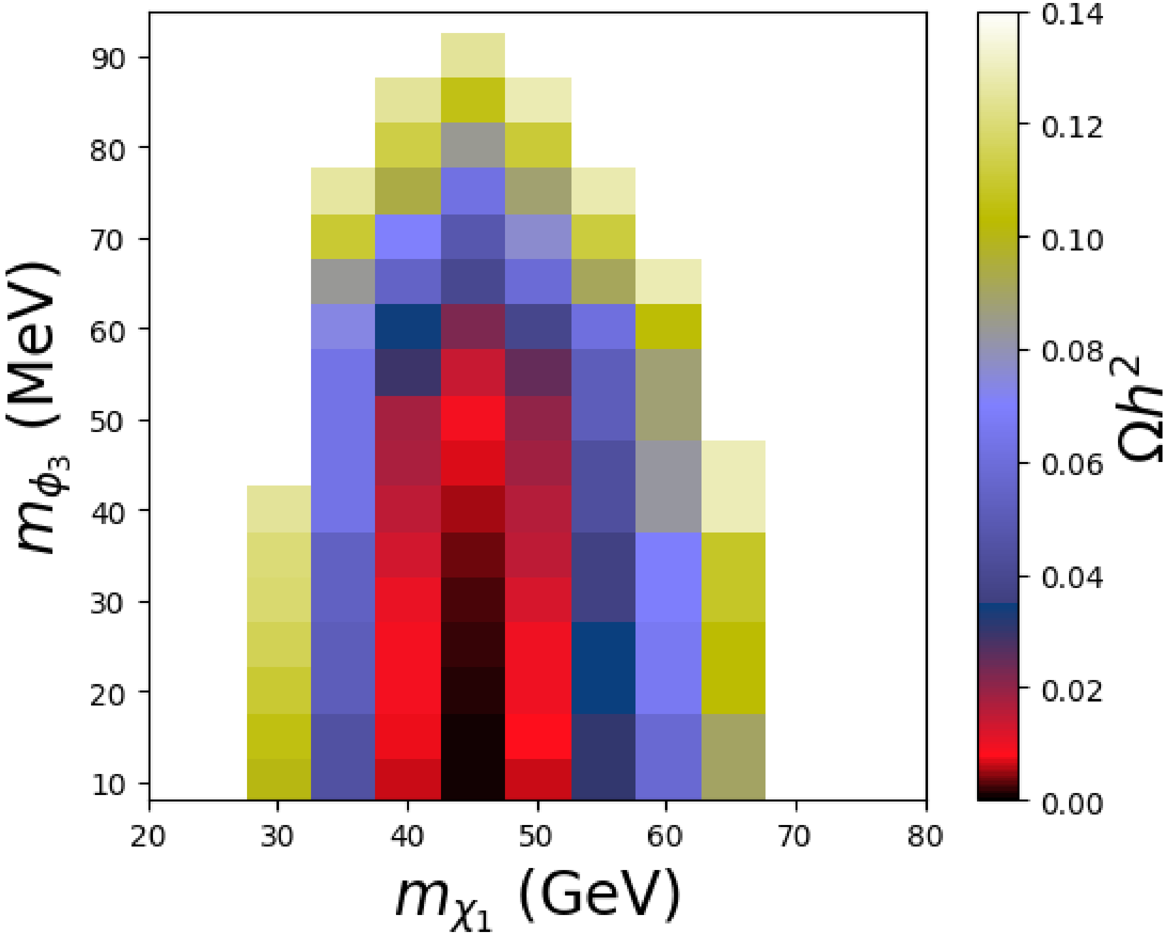




The Scalar DM ϕ_3 with 50 MeV mass, contributes >50% of total DM.

Allowed mass window for fermionic DM χ_1 increased up to 30 GeV – 70 GeV.

Two-component DM: Coupled Boltzmann Equation :

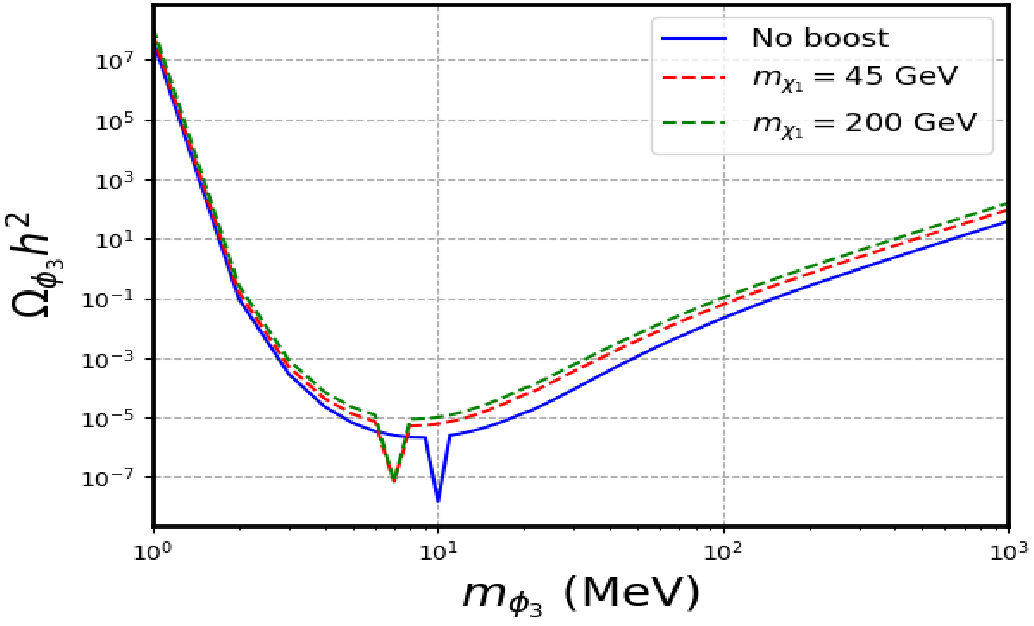


- $\Omega h^2 = 0.1199 \pm 3*0.0027$ (3σ upper limit $\lesssim 0.13$ for the relic density measured by the Planck experiment) is used.
- The yellowish-green makes a boundary on the $m\chi1 - m\phi3$ plane for the under-abundant relic density.
- The white region is ruled out due to the over-abundance of the relic density.

Boosted DM:

$$s = 4m_{\phi_3}^2 + 4m_{\phi_3}^2\left(1 - \frac{1}{\gamma_{\phi_3}^2}\right)$$

$$\gamma_{\phi_3} \sim \frac{m_{\chi_1}}{m_{\phi_3}}$$



No boost case -> $\gamma_{\phi 3} = 1$

resonance condition $s = m_H^2$

or, $m_{\phi_3} = m_H/2$

m_H = 20 MeV is taken as a benchmark

Resonance is due to the H-dominated "s" channel annihilation.

With boost case, for say $m_{\chi 1} = 45$ GeV

The COM energy $s \approx 8m_{\phi_3}^2$

Thus, the resonance condition $s = m_H^2$

gives, $m_{\phi_3} = m_H/(2\sqrt{2})$

Conclusion:

- ***Goal:*** Relic aspects study of Two-Component DM (Depending on a particular BSM Model).

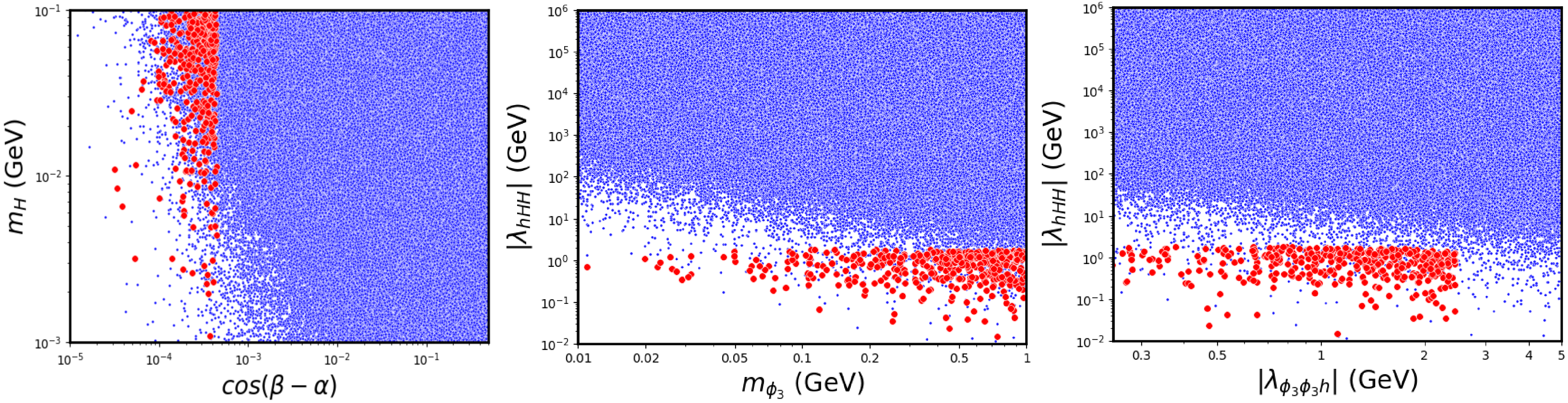
- ***What we are doing:*** The DM-DM interaction is allowed through the Higgs portal, which leads to a two-component model. We showed that the relic aspects change in the **Boosted** case due to the DM-DM interaction.

- ***Final Results:*** We got a mass range for the two DM components and can comment that for some particular choice of masses, the **light scalar DM contributes >50% of total DM**.

Thank You

Theoretical constraints and Benchmark Points :

- Theoretical constraints such as stability of vacuum and tree-level perturbative unitarity.
- The Higgs invisible bound. SM Higgs boson (h) (125 GeV) invisible BR is $<10\%$. **arxiv:** 2303.01214
- Z invisible bound.



We chose mH= 20 MeV. Also checked other values (50,100) MeV. No such variation in relic density observed, other than the shift of resonance drop.

Parameter Space :

The chosen parameter space for our work is,

Benchmark point							
m_H	m_h	α	$\tan\beta$	κ_1	κ_2	Y_ν	m_{N_R}
20 MeV	125 GeV	89.998	1.8×10^{-4}	0.01	0.002	1	10 MeV

A few selected couplings						
λ_{hHH} (GeV)	λ_{hhH} (GeV)	λ_{hhh} (GeV)	$\lambda_{\phi_3\phi_3 h}$ (GeV)	$\lambda_{\phi_3\phi_3 H}$ (GeV)	$\lambda_{\nu_L N_R h}$	$\lambda_{\nu_L N_R H}$
-1.04	0.001	63.5	2.45	3.3×10^{-4}	-2.83×10^{-5}	0.70