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

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Reference:

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 for 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:

Two Higgs doublet model
ν2HDM. Φ_1 and ϕ_2

+

Scalar singlet ϕ_3

+

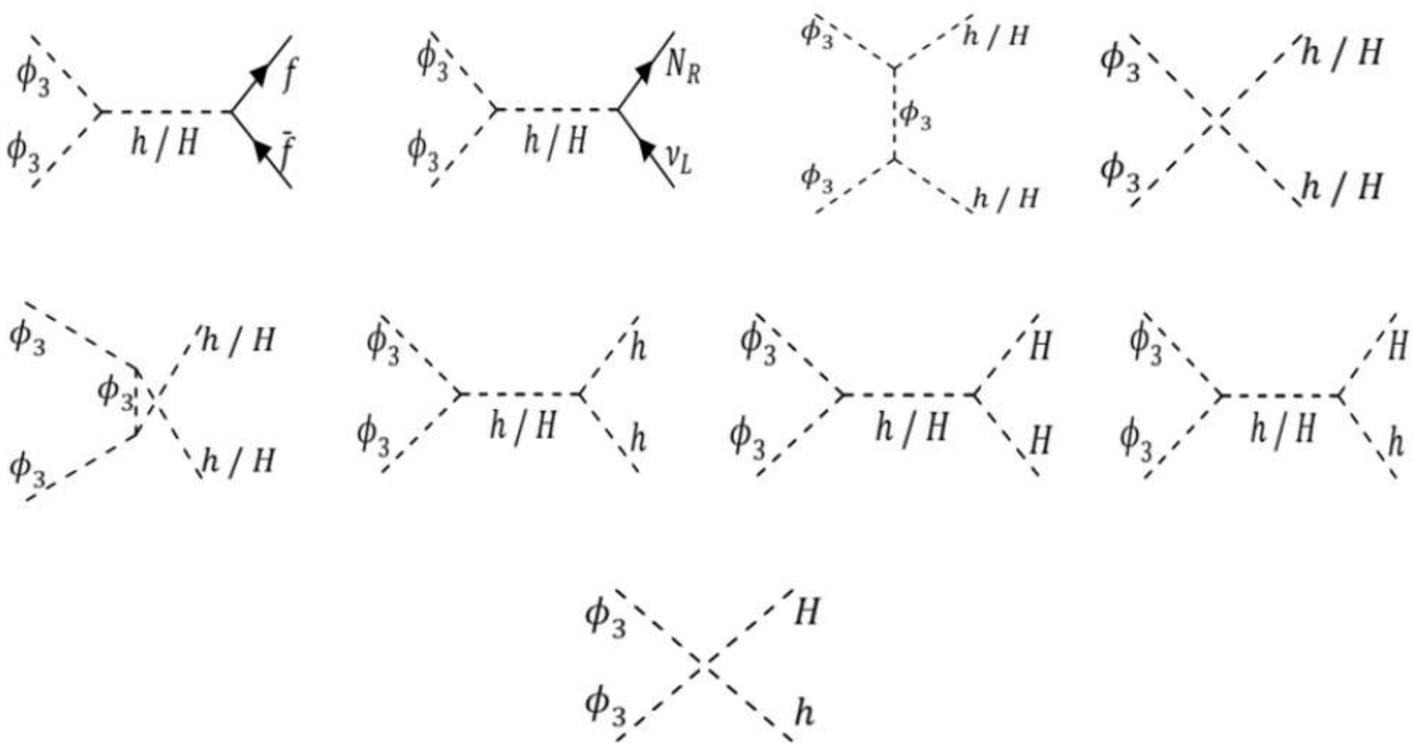
Vector-like doublet **N**
Vector-like singlet χ

Particle Name	$SU(2)_L$ Charges	$U(1)_Y$ Charges	Z_2 Charges
Scalar Fields			
Φ_1	2	1	1
Φ_2	2	1	-1
ϕ_3	1	0	-1
Fermionic Fields			
N	2	-1	-1
χ	1	0	-1

Dark Matter: Relic Density Aspects:

For each of the DM components, the relic density is determined by the Boltzmann equation which is driven by the corresponding DM annihilation cross-section.

Scalar DM ϕ_3:

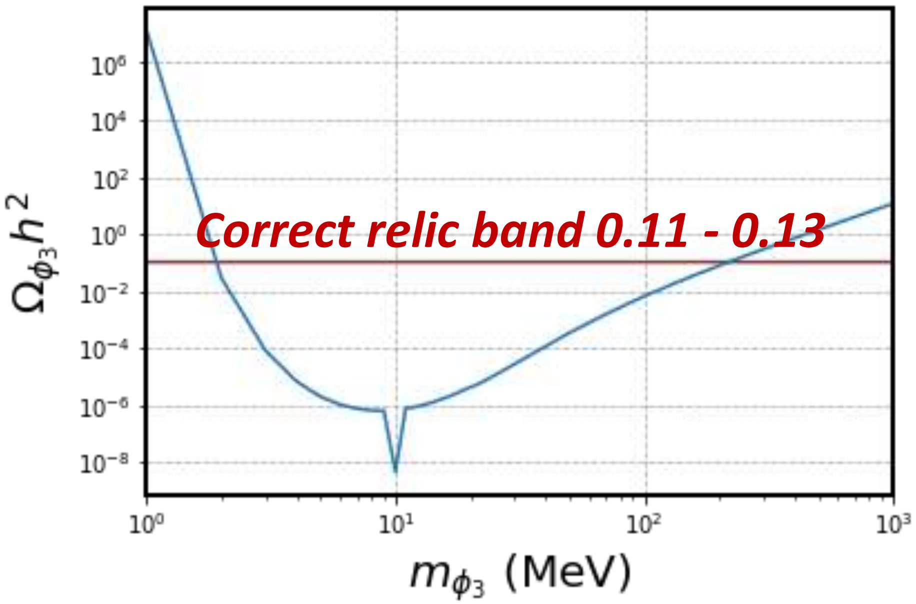


$$\sigma_{\phi_3} = \sigma(s)_{\phi_3\phi_3\to f\bar{f}} + \sigma(s)_{\phi_3\phi_3\to N_R\nu_L} + \sigma(s)_{\phi_3\phi_3\to HH} + \sigma(s)_{\phi_3\phi_3\to hh} + \sigma(s)_{\phi_3\phi_3\to hH}$$

Dark Matter: Relic Density Aspects:

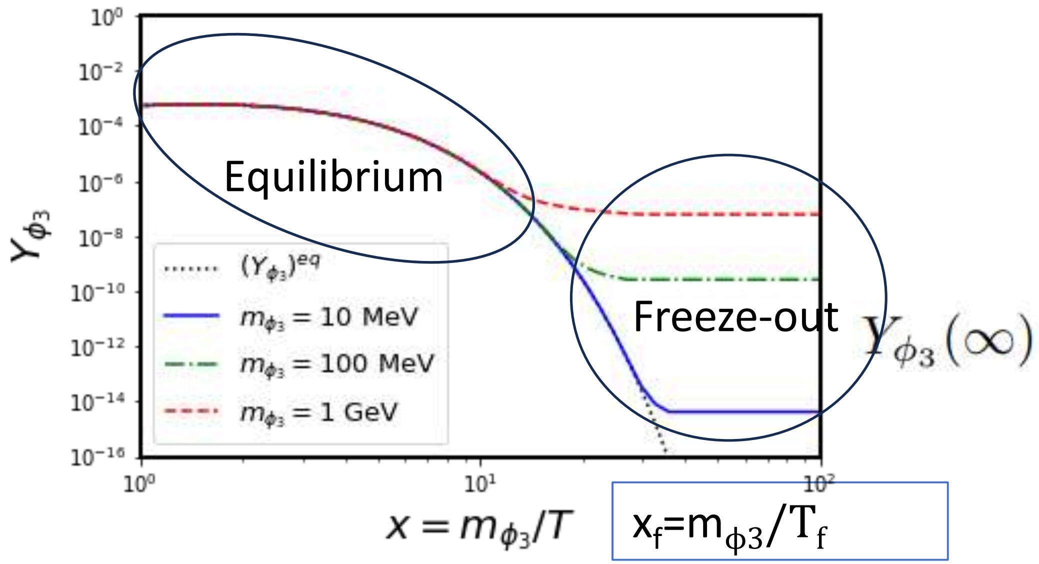
$$\Omega h^2 = \frac{2.14\times 10^9\ \text{GeV}^{-1}}{\sqrt{g_*}\ M_{pl}}\frac{1}{J(x_f)}$$

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



Under abundant window 2 MeV – 200 MeV

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



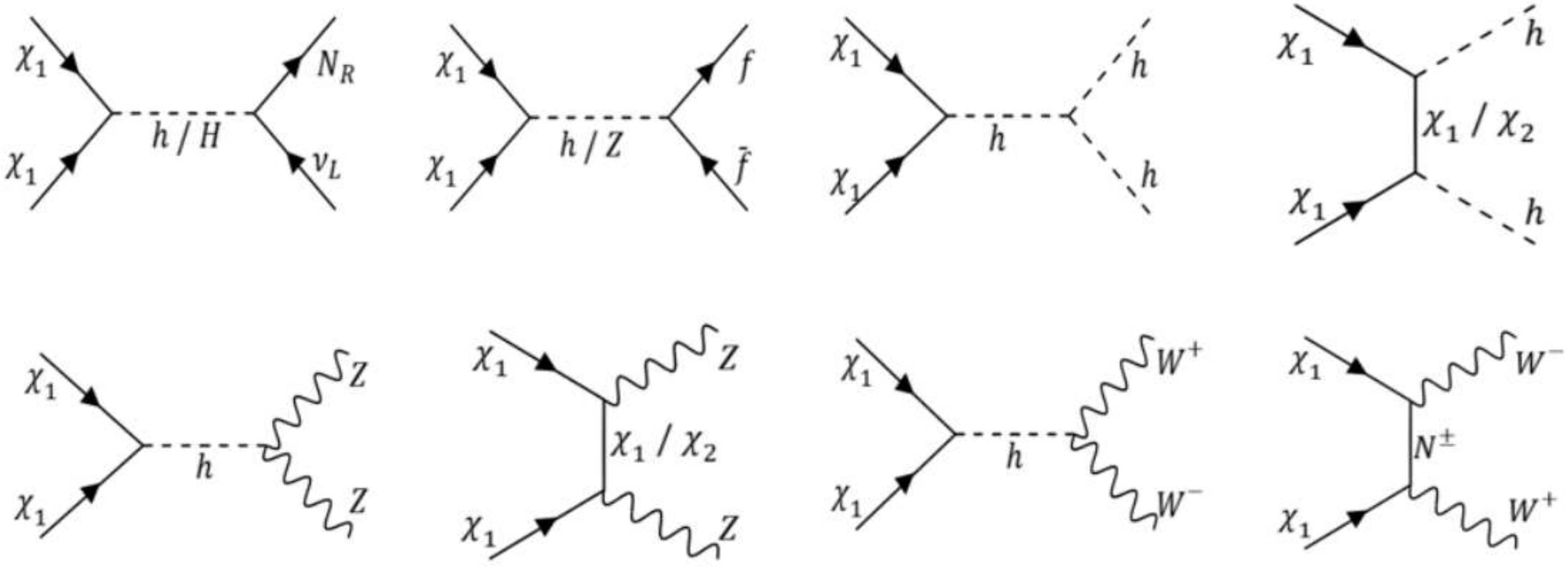
$x_f = m_{\phi 3}/T_f$

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

Scalar DM	
Mass	Relic density
10 MeV	7.70×10^{-9}
100 MeV	6.66×10^{-3}
1 GeV	11.7

Dark Matter: Relic Density Aspects:

Fermionic DM χ_1:

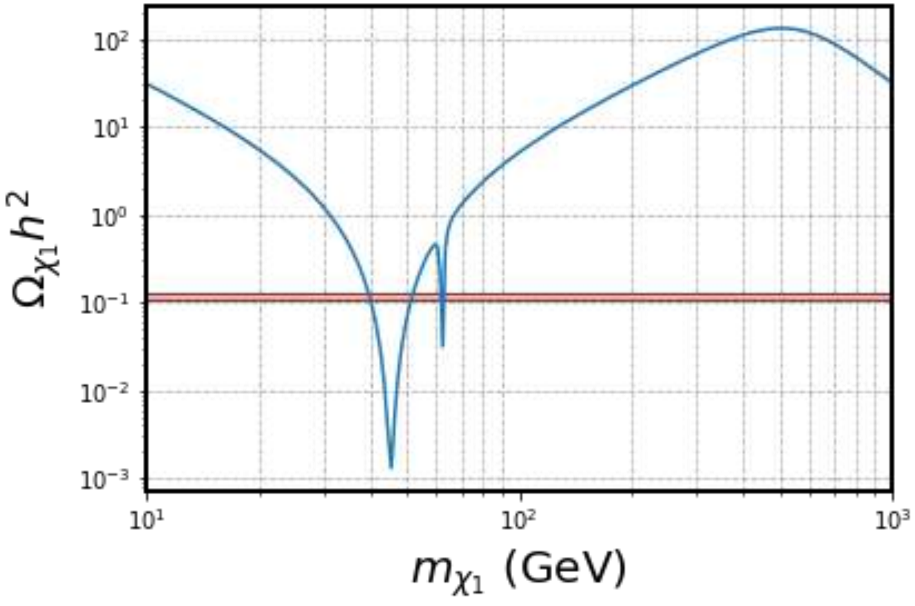


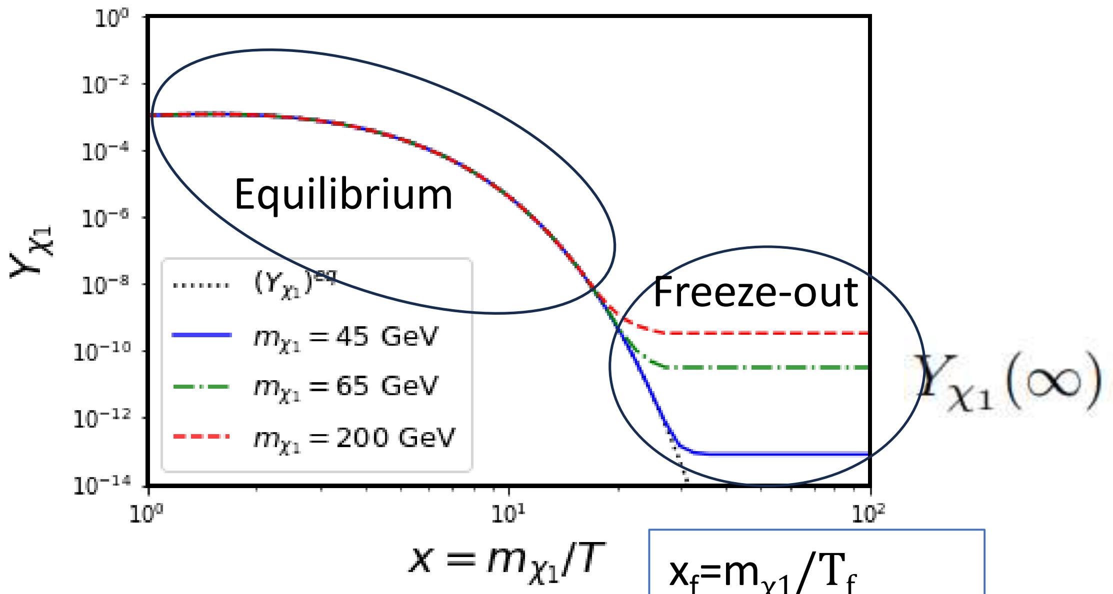
$$\sigma_{\chi 1} = \sigma(s)_{\chi_1\chi_1 \to f\bar{f}} + \sigma(s)_{\chi_1\chi_1 \to N_R\nu_L} + \sigma(s)_{\chi_1\chi_1 \to hh} + \sigma(s)_{\chi_1\chi_1 \to ZZ} + \sigma(s)_{\chi_1\chi_1 \to W^+W^-}$$

Dark Matter: Relic Density Aspects:

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

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





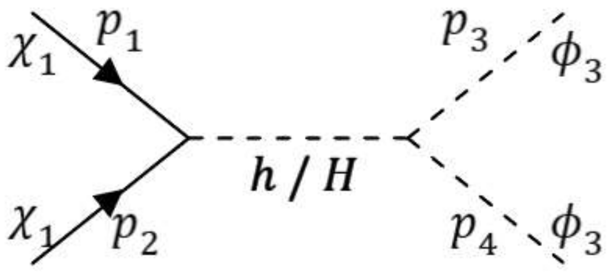
$x_f = m_{\chi_1}/T_f$

Allowed window 40 GeV – 50 GeV.

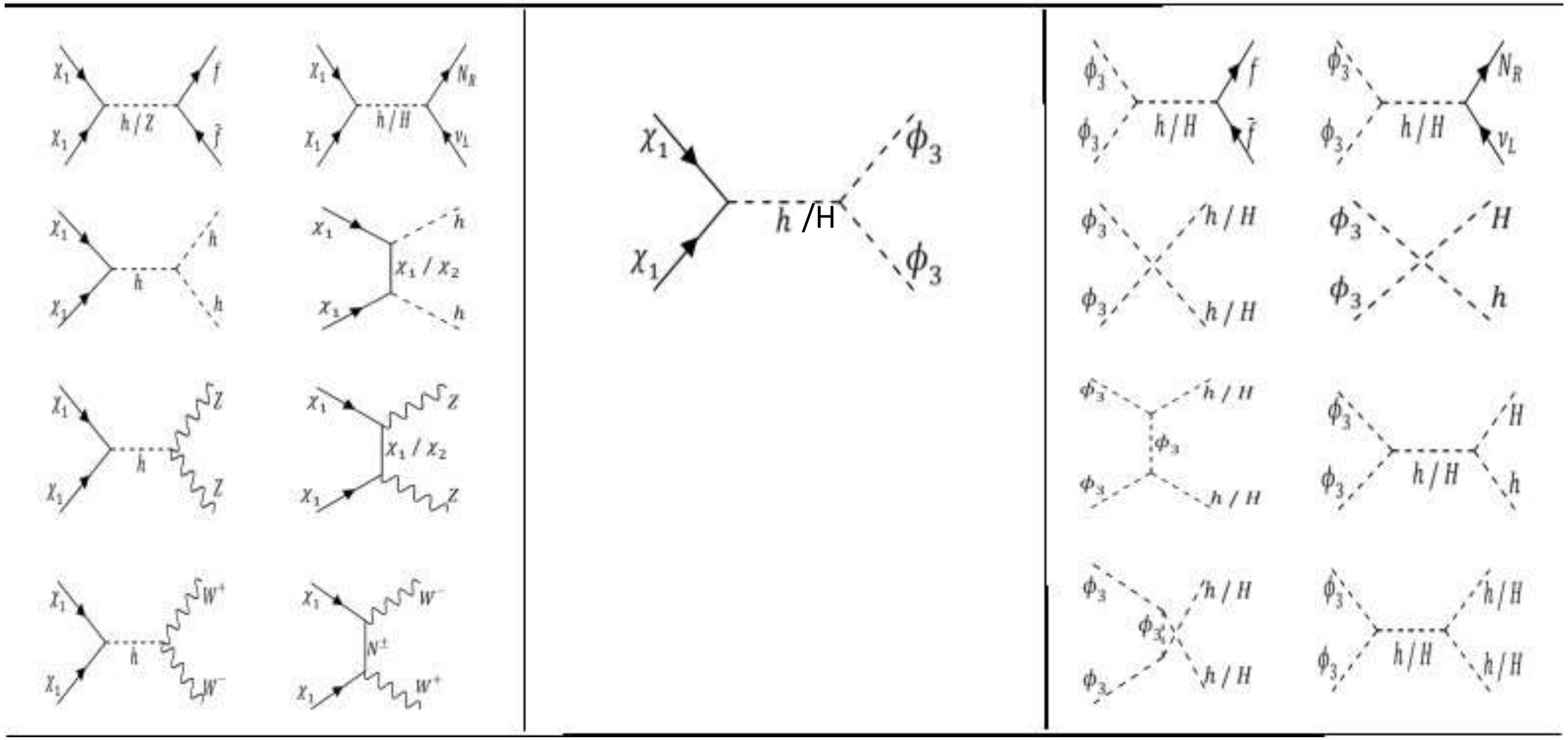
$$\Omega_{\chi_1} h^2 = \frac{m_{\chi_1}\; s_0\; Y_{\chi_1}(\infty)}{\rho_c/h^2}$$

Fermion DM	
Mass	Relic density
45 GeV	1.8×10^{-3}
65 GeV	0.59
200 GeV	19.26

Two-component DM: Coupled Boltzmann Equation :



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

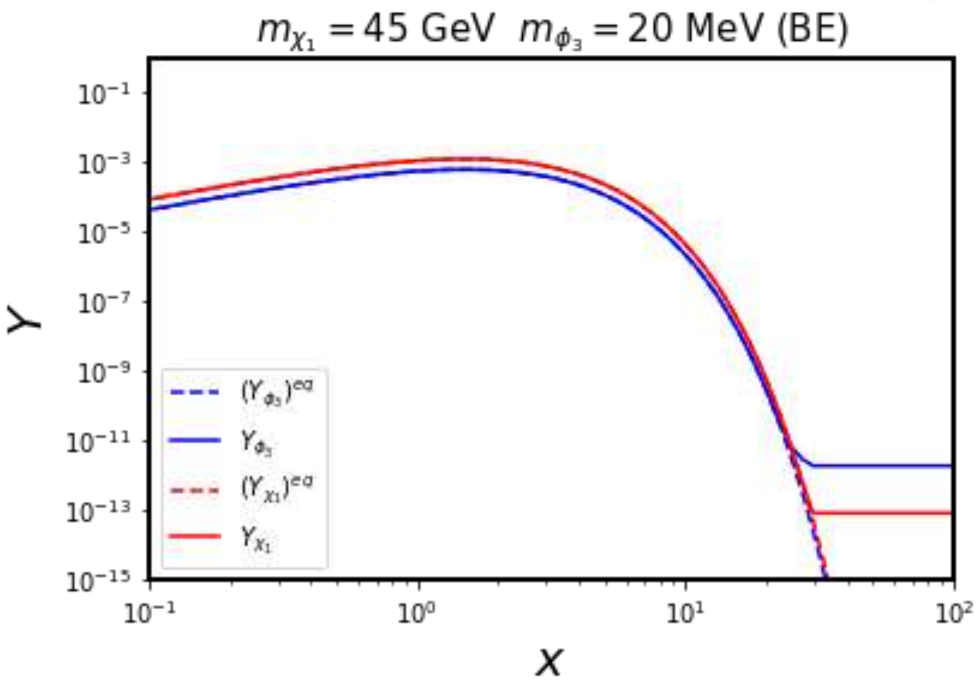


Two-component DM: Coupled Boltzmann Equation :

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

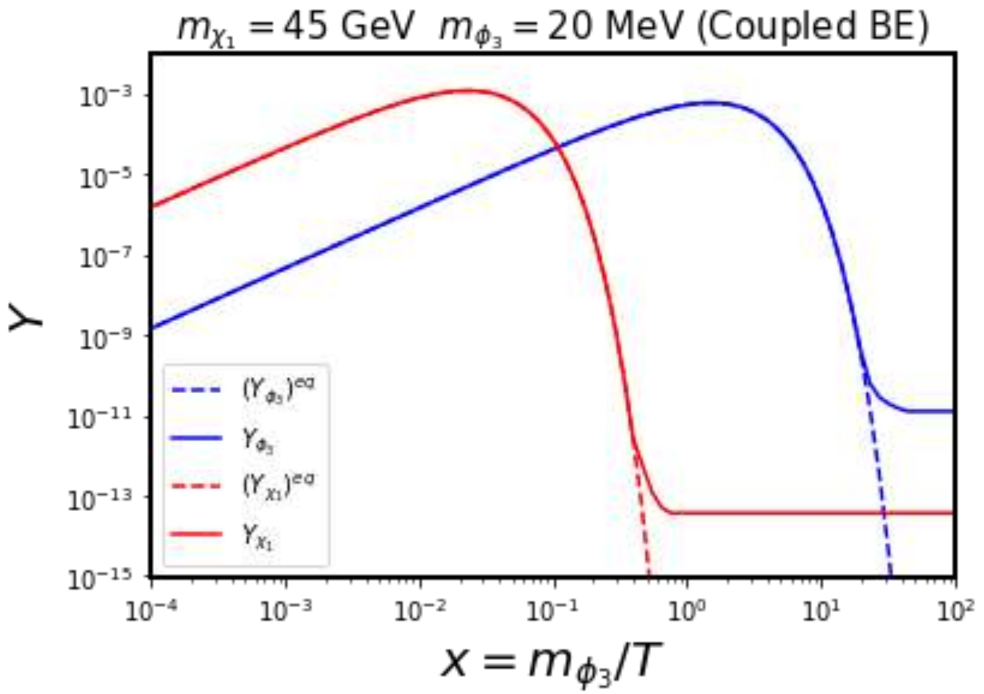
$$\frac{dY_{\phi_3}}{dx} = -\frac{\lambda_{\phi}}{x^2}\left(Y_{\phi_3}^2 - Y_{\phi_3,\mathrm{eq}}^2\right) + \frac{\lambda_{\chi\phi}}{x^2}\left(Y_{\chi_1}^2 - Y_{\phi_3}^2\frac{Y_{\chi_1,\mathrm{eq}}^2}{Y_{\phi_3,\mathrm{eq}}^2}\right)$$

Scaling with comoving density $Y_i = n_i/s$, and $x = m_{\phi3}/T$,



$\Omega_{\chi_1}h^2 =$ **1.8 * 10^-3**

$\Omega_{\phi_3}h^2 =$ **8.69 * 10^-6**

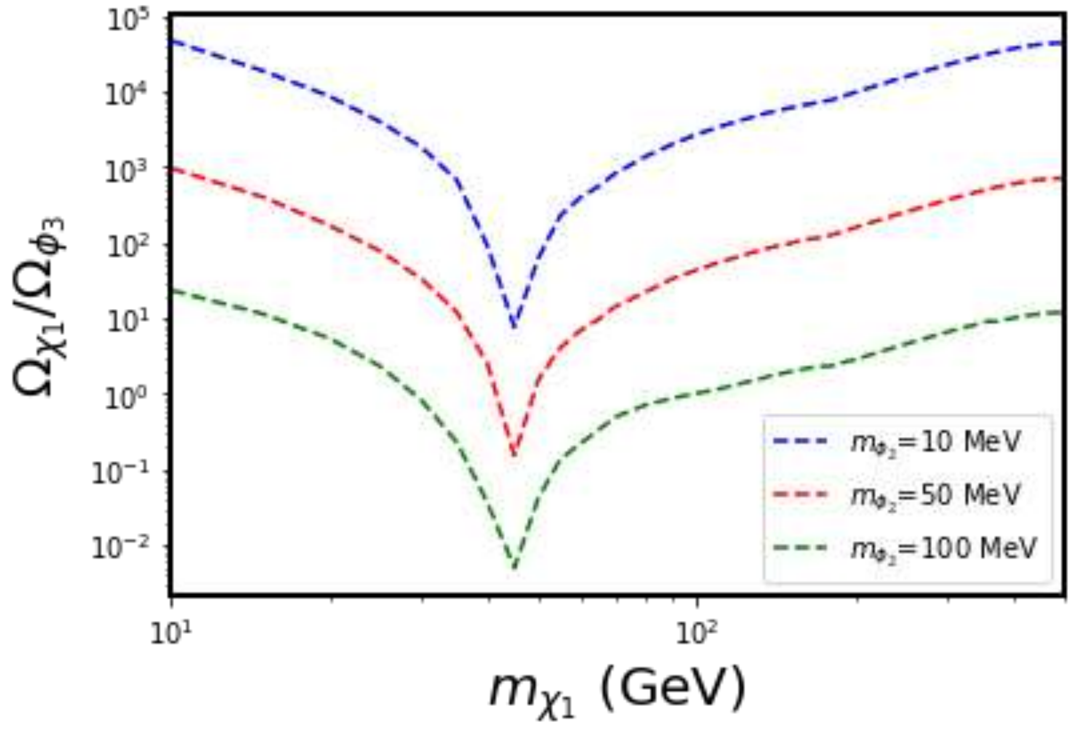


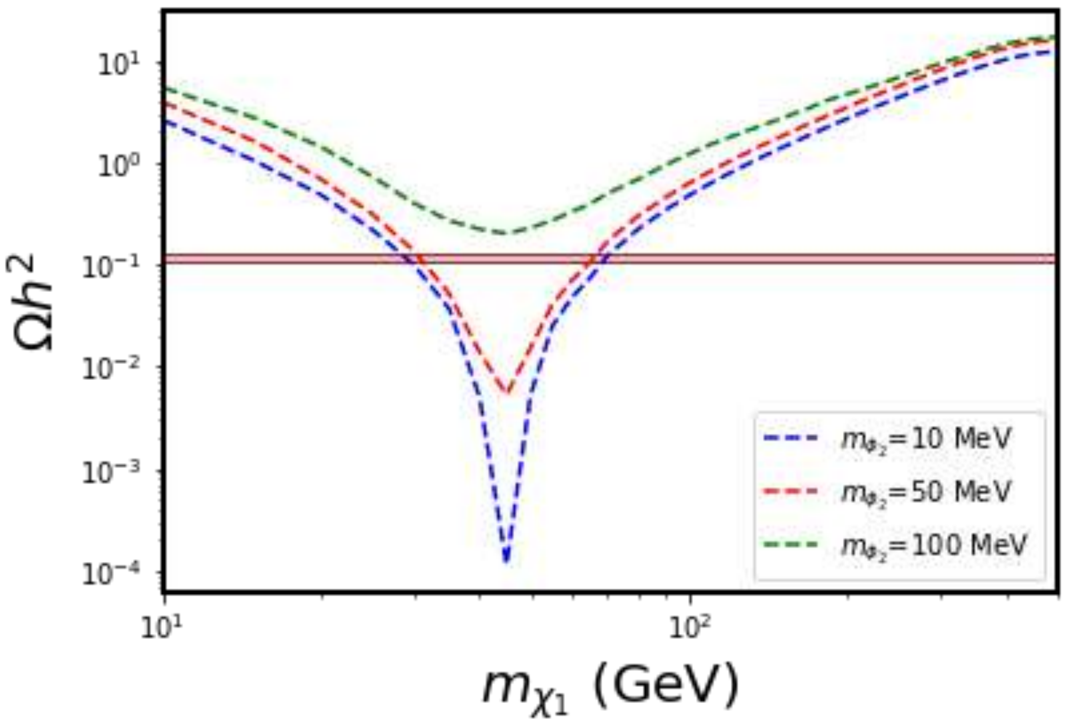
$\Omega_{\chi_1}h^2 =$ **5.6 * 10^-4**

$\Omega_{\phi_3}h^2 =$ **5.2 * 10^-5**

$\Omega h^2 = \Omega_{\chi_1}h^2 + \Omega_{\phi_3}h^2 =$ **6.12 * 10^-4**

Two-component DM: Coupled Boltzmann Equation :





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

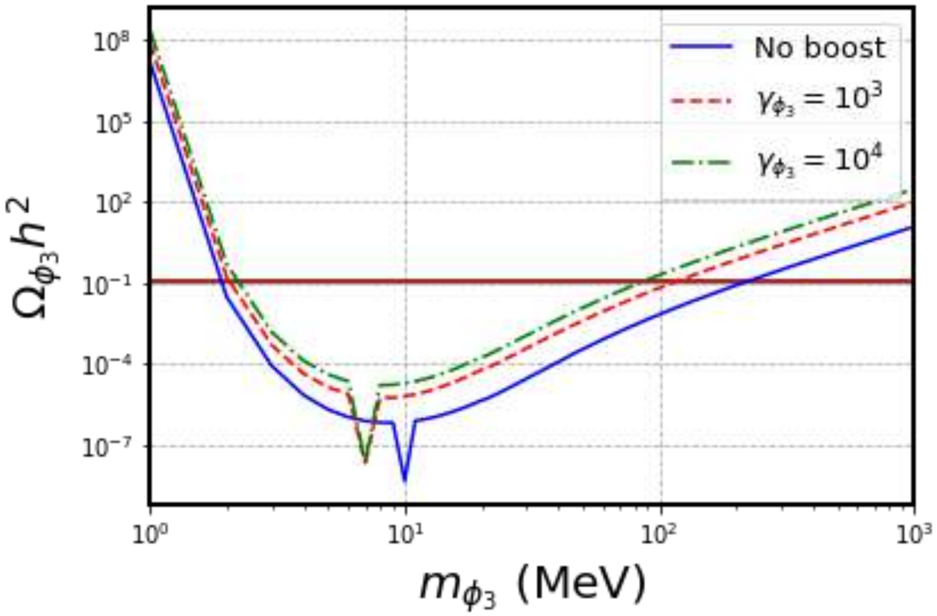
Allowed mass window for fermionic DM χ_1 increased up to 30 GeV – 69 GeV.

Boosted DM:

$$s = 4m_{\phi_3}^2 + 4m_{\phi_3}^2 v_{\phi_3}^2$$

or

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



No boost is obtained by putting $v_{\phi 3}=0$ or $\gamma_{\phi 3}=1$ in

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 $\gamma_{\phi_3} = 10^4$

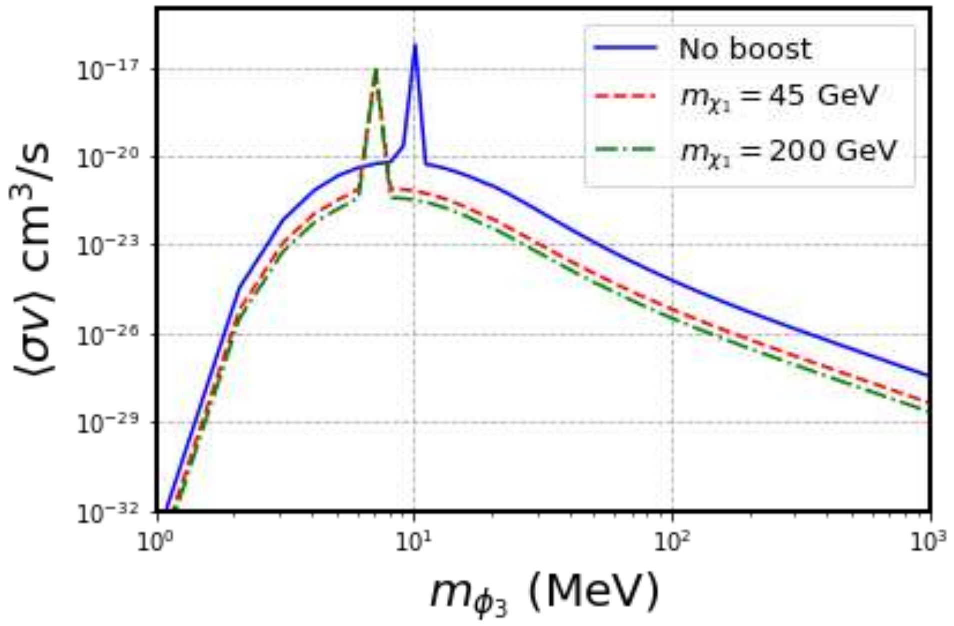
The COM energy $s \approx 8m_{\phi_3}^2$

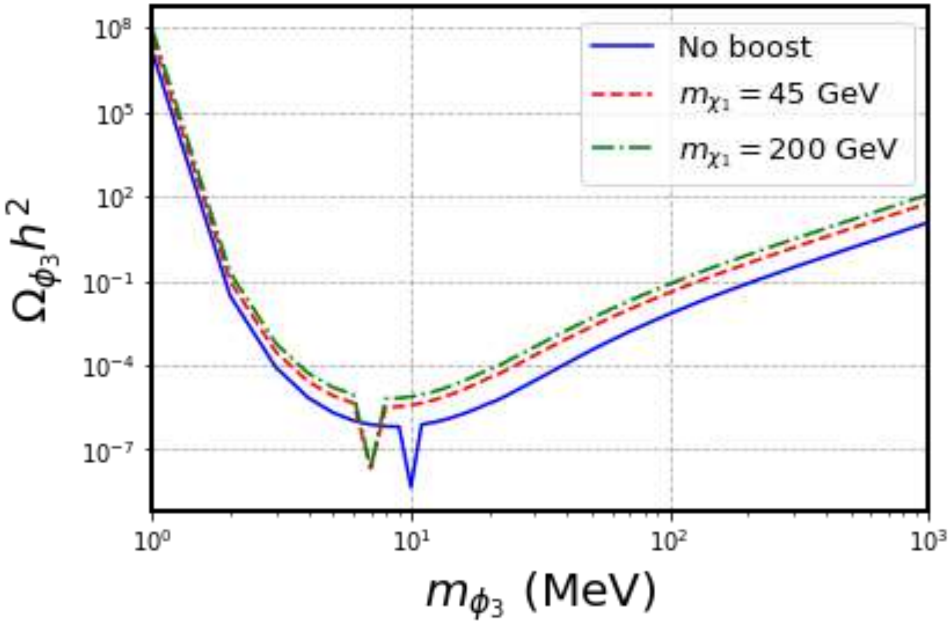
Thus, the resonance condition $s = m_H^2$

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

Boosted DM:

Thus the COM energy expressed as, $s = 4m_{\phi_3}^2 + 4m_{\phi_3}^2\left(1 - \frac{m_{\phi_3}^2}{m_{\chi_1}^2}\left(1 - v_{\chi_1}^2\right)\right)$ $v_{\chi 1} = 220\ \mathrm{Km/s}$





Cross-section $\propto 1/s$ → Cross-section decreases → Relic density increases

Future direction:

- In Direct/Indirect Detection experiments the DM collides with either the electron/nucleon of the detector atom, producing a recoil energy to be detected by the detectors.
- The roadblock for sub-GeV DM is due to its small mass it can only generate very small recoil energy.
- By boosting the DM, although being light mass, it can transfer a large amount of energy to the recoil electron/nucleon; making it easy to detect.
- The challenge to detect the boosted DM is, that the flux of boosted DM is small and nearly mono-energetic, and large volume detectors are preferred.
- We aim to discuss the detection prospect of the MeV scalar dark matter in detail in an upcoming work.

Conclusion:

- Relic density is an important quantity to knowing DM
- Two dark sector particles can interact through the Higgs portal
- Two-component scenario allowed **>50 %** boosted scalar DM as a favorable DM candidate.
- Boosting a lower mass DM to probe further lower region. Compared to the **(2MeV – 200 MeV)** allowed mass window for single scalar relic density, the boosted scalar relic density gives a **(2.5 MeV – 95 MeV)** mass window.
- Boost helps to detect a low-mass DM in the DD experiments.

Thank You

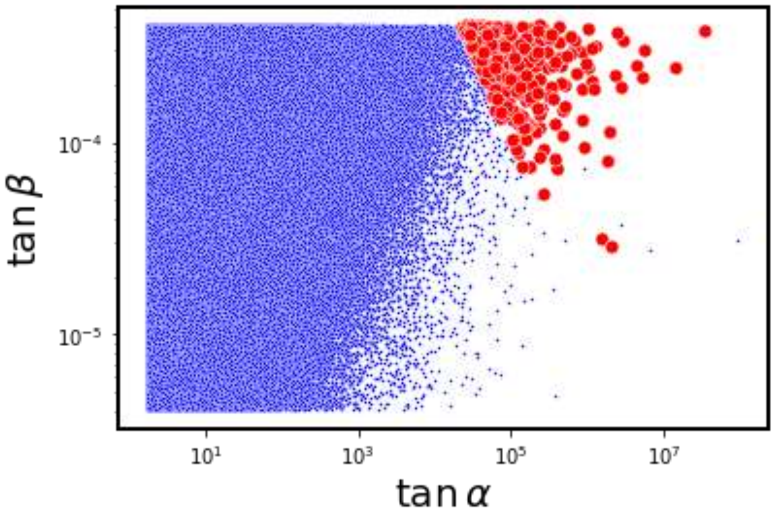
Backup

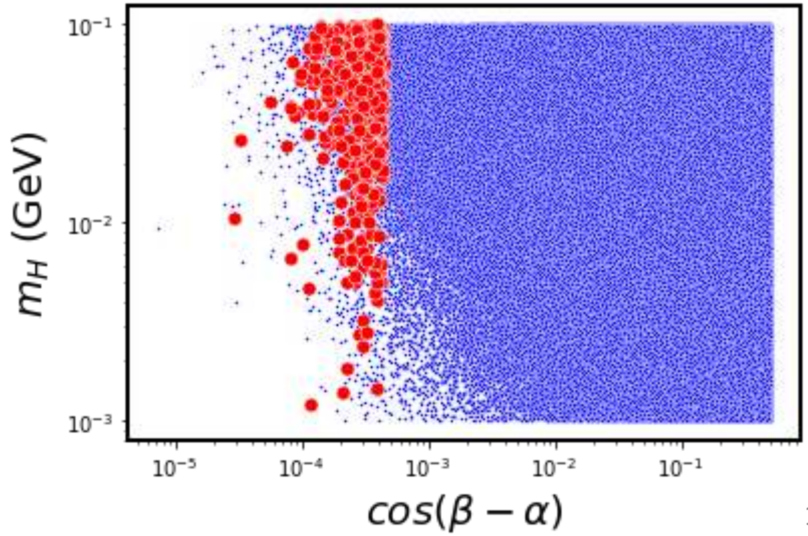
Theoretical constraints and Benchmark Points:

- 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 $<20\%$.
- Z invisible bound.

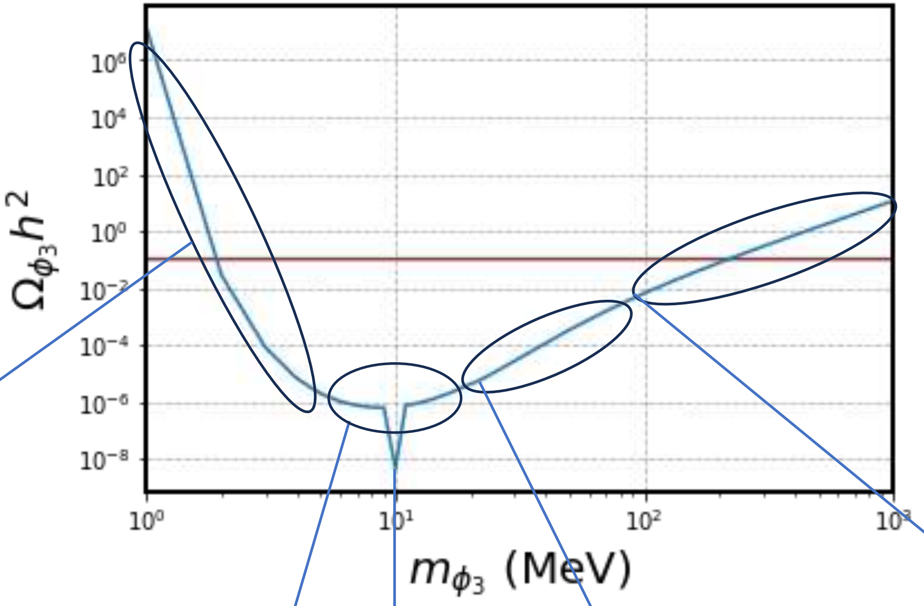
Based on the theoretical constraints, and Higgs invisible BR, we scan over the parameter space

$$\begin{aligned} 1\ \text{MeV} < &\ v_2 < 100\ \text{MeV}, \\ 1\ \text{MeV} < &\ m_H < 100\ \text{MeV} \\ -\pi/2 < &\ \alpha < \pi/2 \end{aligned}$$





Scalar Dark Matter Relic Density:



$$\sqrt{s - 4m_i^2}$$

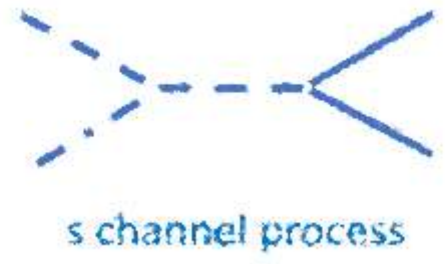
$\phi_3\phi_3 \rightarrow ee(bar)$, $uu(bar)$, $dd(bar)$

$\phi_3\phi_3 \rightarrow N_R\, \nu_L$

$\phi_3\phi_3 \rightarrow HH$

$\phi_3\phi_3 \rightarrow ss(bar)$, $\mu\mu(bar)$, HH

$$\sigma \propto \frac{1}{(s - mH^2)^2}$$



Parameter for VLL DM:

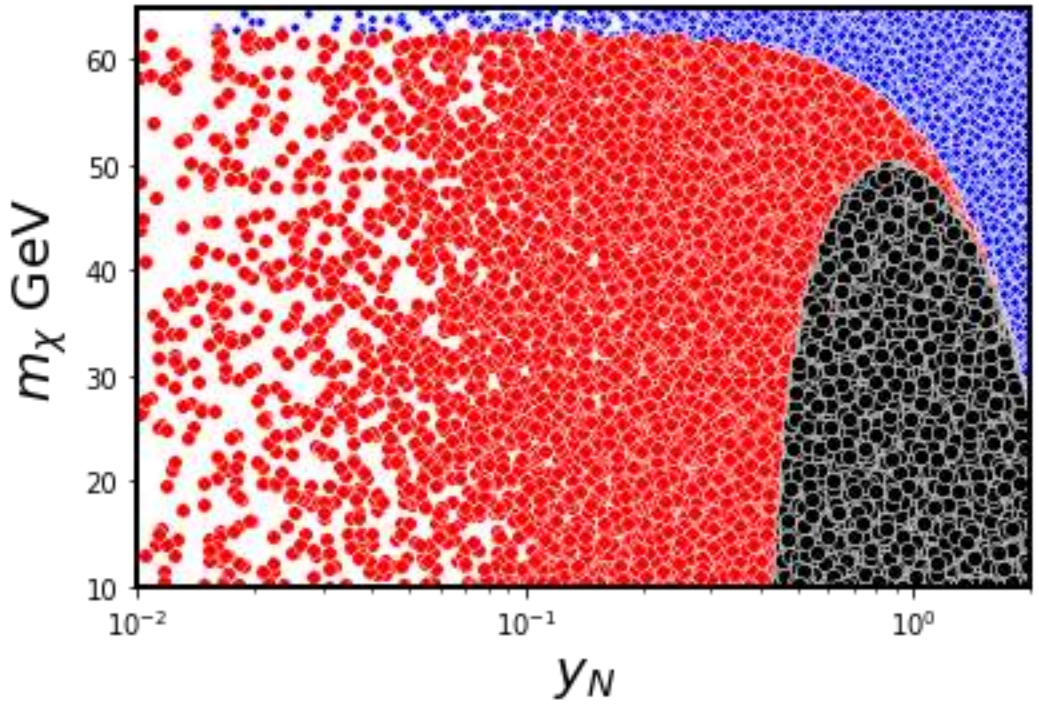
$$L_{VLL} = m_N \bar{N} N + m_\chi \bar{\chi}\chi + y_N \bar{N} \tilde{\Phi_1} \chi + h.c.$$

$$L_{VLL}^{mass} = m_N \bar{N}_- N_+ + (\bar{N_0} \;\; \bar{\chi}) \begin{pmatrix} m_N & \frac{y_N v_1}{\sqrt{2}} \\ \frac{y_N v_1}{\sqrt{2}} & m_\chi \end{pmatrix} \begin{pmatrix} N_0 \\ \chi \end{pmatrix}$$

$$m_{\chi_1} = m_\chi c_\theta^2 - m_N s_\theta^2 - \frac{y_N \; v_1}{\sqrt{2}} \sin 2\theta$$
$$m_{\chi_2} = m_N c_\theta^2 + m_\chi s_\theta^2 + \frac{y_N \; v_1}{\sqrt{2}} \sin 2\theta$$

$$N_0 = c_\theta \chi_2 - s_\theta \chi_1$$
$$\chi = s_\theta \chi_2 + c_\theta \chi_1$$

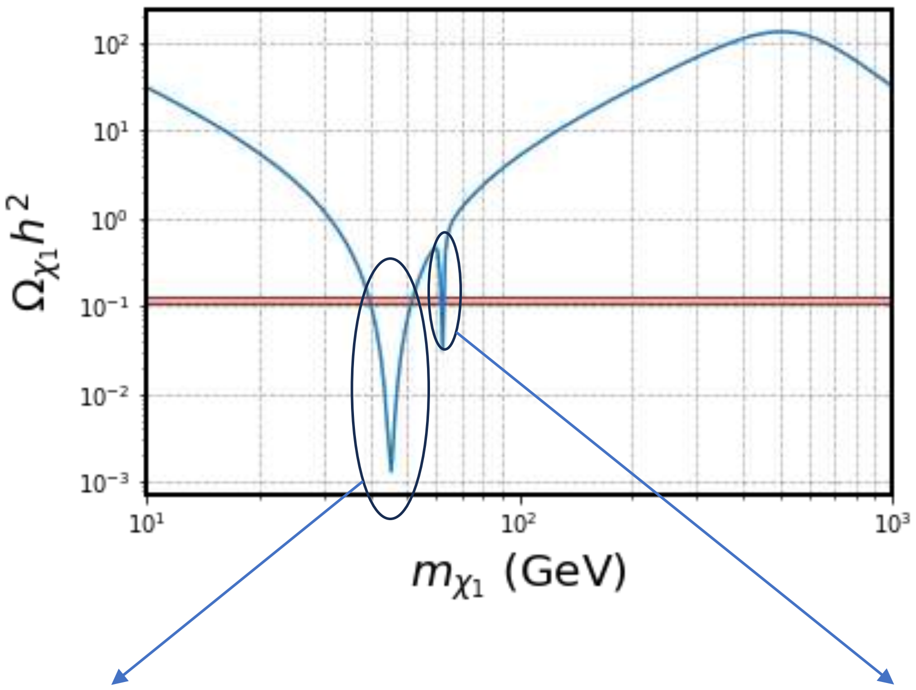
$$\tan 2\theta = \frac{\sqrt{2}(y_N \; v_1)}{(m_N - m_\chi)}$$



$$\Gamma(h \to \chi_1 \chi_1) = \frac{1}{16\,\pi} (y_N \;\; \sin 2\theta)^2 \; m_h \left(1 - \frac{4 m_{\chi_1}^2}{m_h^2}\right)^{3/2}$$

Conclusion: y_N can not be more than 0.42

Fermion Dark Matter Relic Density:



Parameters:

$y_N = 0.4$
$m_N = 3$ TeV

$$\sigma \propto \frac{1}{(s - mZ^2)^2}$$

$$\sigma \propto \frac{1}{(s - mh^2)^2}$$

Dark Matter: Relic Density Aspects:

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

The BE is expressed for the scalar DM ϕ_3,

$$\frac{dn_{\phi_3}}{dt} + 3Hn_{\phi_3} = -\langle\sigma_{\phi_3}v\rangle(n^2_{\phi_3} - n^2_{\phi_3,\mathrm{eq}})$$

Change of number density

Effect of Universe expansion rate

Number density decreasing from equilibrium number density. '-' sign suggests

with Y=n/s, and x=m/T scaling factor,

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

where the thermally averaged cross-section of scalar DM ϕ_3 is,

$$\langle\sigma v\rangle_{\phi_3\phi_3\to SM} = \frac{x}{8m^5_{\phi_3}K^2_2\left(x\right)}\int_{4m^2_{\phi_3}}^{\infty} \sigma(s)_{\phi_3\phi_3\to SM}\times(s-4m^2_{\phi_3})\sqrt{s}K_1\left(\frac{x\sqrt{s}}{m_{\phi_3}}\right)ds$$

Dark Matter: Relic Density Aspects:

The BE is expressed for the fermionic DM $\chi1$,

$$\frac{dn_{\chi_1}}{dt} + 3Hn_{\chi_1} = -\frac{1}{2}\langle\sigma_{\chi_1} v\rangle(n^2_{\chi_1} - n^2_{\chi_1,\mathrm{eq}})$$

with Y=n/s, and x=m/T scaling factor,

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

where the thermally averaged cross-section of fermionic DM $\chi1$ is,

$$\langle\sigma v\rangle_{\chi_1\chi_1\to SM} = \frac{x}{8m^5_{\phi_3}K^2_2\left(x\right)}\int^{\infty}_{4m^2_{\chi_1}} \sigma(s)_{\chi_1\chi_1\to SM} \times (s - 4m^2_{\chi_1})\sqrt{s}K_1\left(\frac{x\sqrt{s}}{m_{\chi_1}}\right)ds$$

But due to x= $m_{\chi1}/T >> 1$, it is greatly simplified with,

$$\langle\sigma v\rangle_{\chi_1\chi_1\to SM} \simeq \sigma_{\chi_1}(s) \times v = \sigma_{\chi_1}(s) \times \frac{\sqrt{s - 4m^2_{\chi_1}}}{m_{\chi_1}} = \langle\sigma v\rangle$$

Two-component DM: Coupled Boltzmann Equation :

$$\frac{dn_{\chi_1}}{dt} + 3Hn_{\chi_1} = -\frac{1}{2}\langle\sigma_{\chi_1\chi_1\to\phi_3\phi_3}v\rangle\left(n_{\chi_1}^2 - n_{\phi_3}^2\frac{n_{\chi_1,\mathrm{eq}}^2}{n_{\phi_3,\mathrm{eq}}^2}\right) - \frac{1}{2}\langle\sigma_{\chi_1}v\rangle\left(n_{\chi_1}^2 - n_{\chi_1,\mathrm{eq}}^2\right)$$

$$\frac{dn_{\phi_3}}{dt} + 3Hn_{\phi_3} = -\langle\sigma_{\phi_3}v\rangle\left(n_{\phi_3}^2 - n_{\phi_3,\mathrm{eq}}^2\right) - \langle\sigma_{\phi_3\phi_3\to\chi_1\chi_1}v\rangle\left(n_{\phi_3}^2 - n_{\chi_1}^2\frac{n_{\phi_3,\mathrm{eq}}^2}{n_{\chi_1,\mathrm{eq}}^2}\right)$$

Scaling with comoving density $Y_i=n_i/s$, and $x=m_{\phi 3}/T$,

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

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

Where,

$$\lambda_{\chi\phi} = \frac{s(m_{\phi_3})}{H(m_{\phi_3})}\langle\sigma v\rangle_{\chi_1\chi_1\to\phi_3\phi_3}$$

$$\lambda_\chi = \frac{s(m_{\phi_3})}{H(m_{\phi_3})}\langle\sigma_{\chi_1}v\rangle$$

$$\lambda_\phi = \frac{s(m_{\phi_3})}{H(m_{\phi_3})}\langle\sigma_{\phi_3}v\rangle$$

$$Y_{\phi_3,eq} = \frac{0.145}{100}x^{3/2}e^{-x}$$

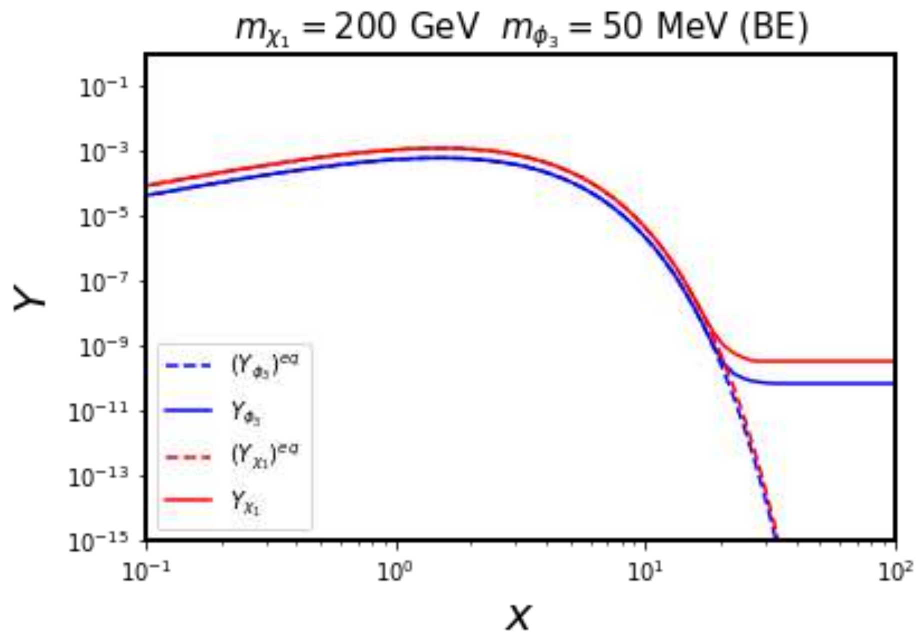
$$Y_{\chi_1,eq} = \frac{0.145\times 2}{100}\left(\frac{m_{\chi_1}}{m_{\phi_3}}\right)^{3/2} x^{3/2}\, e^{-\frac{m_{\chi_1}}{m_{\phi_3}}x}$$

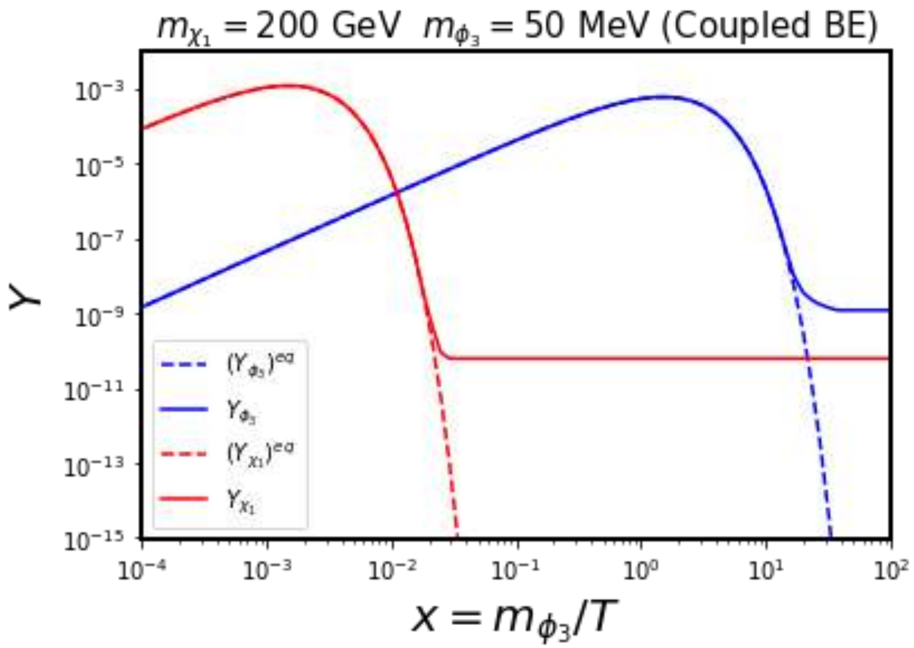
$$s(m_{\phi_3}) = \frac{2\pi^2}{45}g^* m_{\phi_3}^3$$

$$H(m_{\phi_3}) = \frac{\pi}{90}\frac{\sqrt{g^*}}{M_{pl}^r}m_{\phi_3}^2$$

$$M_{pl}^r = 2.44\times 10^{18}\ \mathrm{GeV}$$

Two-component DM: Coupled Boltzmann Equation :





$\Omega_{\chi_1} h^2 =$ 19.26

$\Omega_{\phi_3} h^2 =$ 1.05 *10^-3

$\Omega_{\chi_1} h^2 =$ 3.98

$\Omega_{\phi_3} h^2 =$ 0.028

$\Omega h^2 = \Omega_{\chi_1} h^2 + \Omega_{\phi_3} h^2 =$ 4.00