Features of Multipartite Scalar Dark Matter

by
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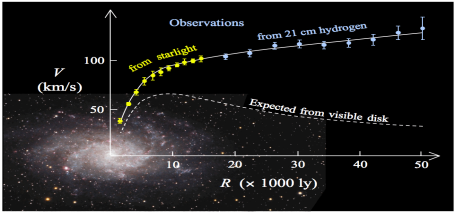
BSM 2021, CFP Zewail City

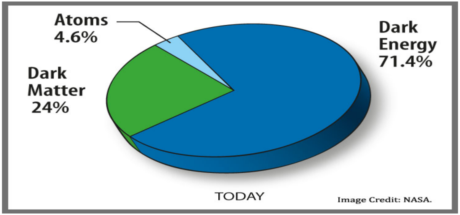
based on

JHEP 2003 (2020) 090 S. Bhattacharya, **P.Ghosh**, A. K. Saha, A. Sil
arXiv: 1905.12583

March 30, 2021



Rotation Curve of Galaxies



WMAP-PLANCK data

- **Properties of DM particles:**
  - ✓ EM charge neutral
  - ✓ Weakly-interacting
  - ✓ stable and Massive

WIMP(Single and Multiparticle nature)

- None of the SM be the suitable candidate of Dark Matter.
- What kind of elementary particles can be Dark Matter ?

$\phi_{\rm DM} = \{\psi^{\rm dark}_{\rm Fermion}, A^{\mu\,\rm dark}_{\rm Boson}, \phi^{\rm dark}_{\rm Scalar}\}$

(dark $\equiv$ EM charge neutral)

- Multicomponent scalar DM scenario: $\{\phi(\text{singlet}),\ \Phi(\text{doublet})\}$

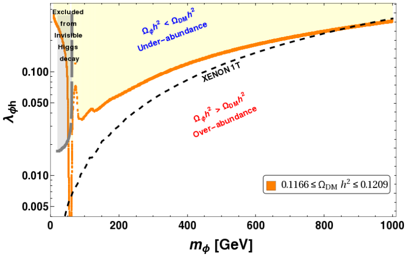
- ϕ be the real singlet scalar DM
- $\mathcal{Z}_2 : \phi \to -\phi$
- Scalar Potential:

$$V(\phi, H) \supset \frac{1}{2}{\mu_\phi}^2\phi^2 + \frac{1}{2}\lambda_{\phi h} H^\dagger H \phi^2$$

- Relic: (annihilation)

$$\phi\ \phi \to \text{SM}\ \ \text{SM}$$

- DD: $\phi\ N \to \phi\ N$ (t channel)



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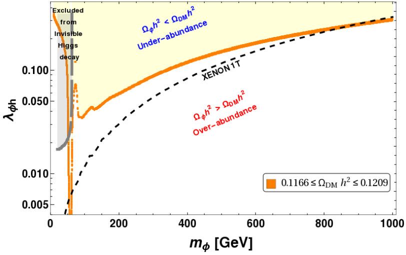


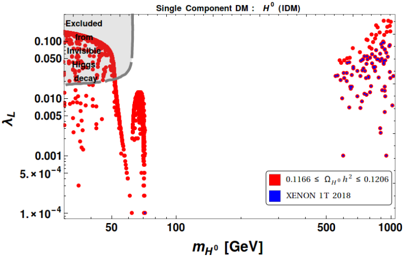
- $\Phi = (H^0,\ \frac{H^+ + iA^0}{\sqrt{2}})$ be the inert doublet scalar DM. $\mathcal{Z}_2 : \Phi \to -\Phi$
- Kinetic Interaction: $|D_\mu\Phi|^2$
- Scalar Potential: $V(\Phi, H)$

$$\supset \mu_\Phi^2(\Phi^\dagger\Phi) + \frac{\lambda_3}{2}[(H^\dagger\Phi)^2 + h.c.]$$
$$+\lambda_2(H^\dagger\Phi)(\Phi^\dagger H) + \lambda_1(H^\dagger H)(\Phi^\dagger\Phi)$$

- Relic: (co-)annihilation

$$H^0\ H^0; H^0\ A^0; H^0\ H^\pm \to \text{SM}\ \ \text{SM}$$

- DD: $H^0\ N \to H^0\ N$ (t channel)

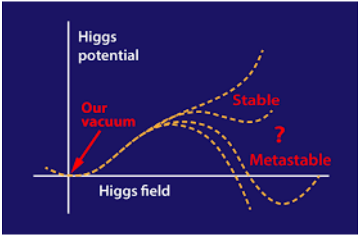


SM Higgs Potential:

$$V(H) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$$

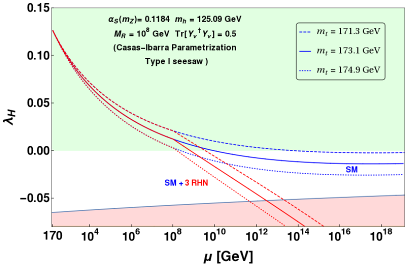
Stable: $\mu_H^2 > 0$ $\lambda_H > 0$

Unstable: $\mu_H^2 > 0$ $\lambda_H < 0$



- One loop beta function for λ_H

$$\begin{aligned}\beta_{\lambda_H} &= +\frac{27}{200}g_1^4 + \frac{9}{20}g_1^2 g_2^2 + \frac{9}{8}g_2^4 \\ &\quad -\frac{9}{5}g_1^2\lambda_H - 9g_2^2\lambda_H + 24\lambda_H^2 \\ &\quad +12\lambda_H y_t^2 - 6y_t^4 \\ &\quad +4\lambda_H \mathrm{Tr}[Y_\nu^\dagger Y_\nu] - 2\mathrm{Tr}[(Y_\nu^\dagger Y_\nu)^2]\end{aligned}$$



$\mathrm{Tr}[Y_\nu^\dagger Y_\nu]$: Casas-Ibarra Parametrization (ref:J.A.Casas and A.Ibarra, NPB 2001.)

$$Y_\nu = \sqrt{2}\,\frac{\sqrt{M_R}}{v}\,\mathcal{O}\,e^{i\mathcal{A}}\,\sqrt{m_\nu^d}\,U_{PMNS}^\dagger$$

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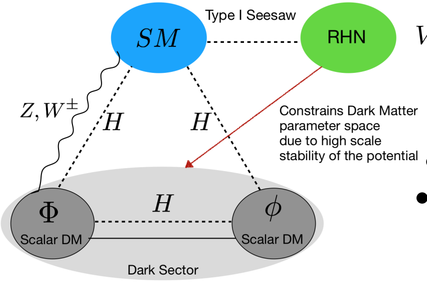
- Can we achieve the absolute vacuum stability or metastability while incorporating light neutrino mass and DM $80 \lesssim m_{H^0}, m_\phi \lesssim 500$ GeV ?

Ans: Yes, one can adress all the issues with the help of Multipartite DM framework where both scalar fields behave as two stable DM candidate.

SM extension : Inert scalar doublet (Φ) and Real scalar singlet (ϕ).

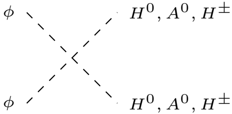
Dark Matters and Neutrinos	$SU(3)_C$	$\times SU(2)_L$	$\times U(1)_Y$	$\times \mathcal{Z}_2$	$\times \mathcal{Z}'_2$
Φ	1	2	-1	-	+
ϕ	1	1	0	+	-
$N_{i=1,2,3}$	1	1	0	+	+



$$V = V(H) + V(\Phi, H) + V(\phi, H) + V(\Phi, \phi)$$

$$V(\Phi, \phi) = \frac{\lambda_c}{2}(\phi^2)\left(\Phi^\dagger \Phi\right)$$

- Stable DMs: $\{\phi, \quad H^0\}$
- DM Conversion

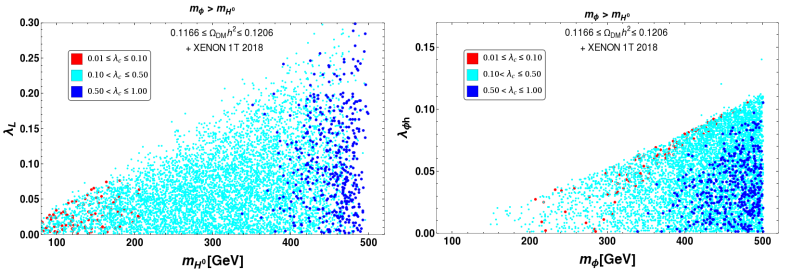


$$\beta_{\lambda_H} = \beta^{SM}_{\lambda_H} + \beta^{DM}_{\lambda_H} + 4\lambda_H \mathrm{Tr}[Y_\nu^\dagger Y_\nu] - 2\mathrm{Tr}[(Y_\nu^\dagger Y_\nu)^2]$$

- Neutrino Mass (Type I Seesaw) $\mathcal{L}^\nu = (Y_\nu)_{ij} l_{L_i} \widetilde{H} N_j + \frac{1}{2} M_{N_{ij}} \overline{N_i} N_j$

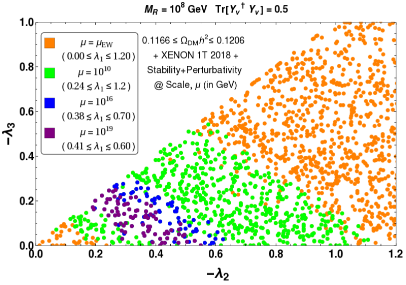
- Stable DM components : $\Omega_{\rm DM}h^2 = \Omega_{H^0}h^2 + \Omega_\phi h^2$
- Direct Detection:

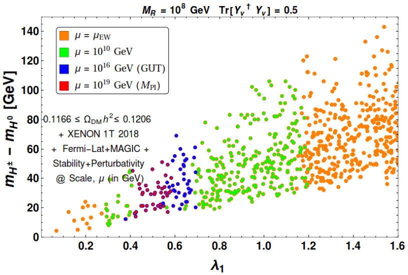
$$\sigma_{\rm eff}^{\rm DD}(\phi) = \left(\Omega_\phi/\Omega_{\rm DM}\right)\sigma_{\{\phi-n\}} \qquad \sigma_{\rm eff}^{\rm DD}(H^0) = \left(\Omega_{H^0}/\Omega_{\rm DM}\right)\sigma_{\{H^0-n\}}$$



- Presence of interacting multicomponent DM scenario, the mass region $80 \lesssim m_{H^0}, m_\phi \lesssim 500$ GeV of both scalar singlet and inert doublet is allowed from relic and direct search bounds.

$$\beta^{(1)}_{\lambda_H} = +\frac{27}{200}g_1^4 + \frac{9}{20}g_1^2g_2^2 + \frac{9}{8}g_2^4 - \frac{9}{5}g_1^2\lambda_H - 9g_2^2\lambda_H + 24\lambda_H^2 + 12\lambda_H y_t^2 - 6y_t^4 + 2\lambda_1^2 + 2\lambda_1\lambda_2 + \lambda_2^2 + \lambda_3^2 + \frac{1}{2}\lambda_{\phi h}^2 + 4\lambda_H \mathrm{Tr}[Y_\nu^\dagger Y_\nu] - 2\mathrm{Tr}[(Y_\nu^\dagger Y_\nu)^2]$$

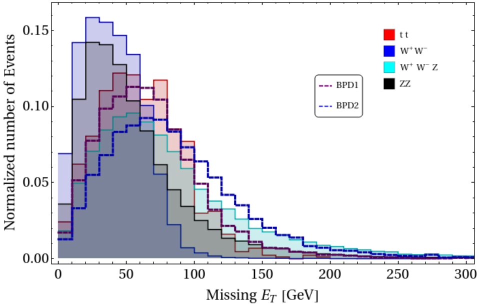


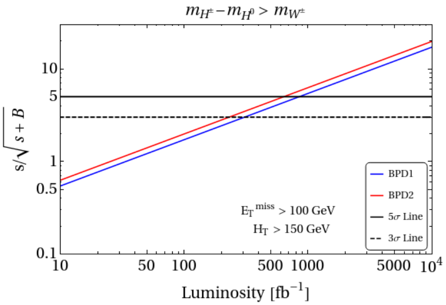


- small values of λ_1 (i.e. small $m_{H^\pm} - m_{H^0}$)are discarded due to stability.
- large values of λ_1 (i.e. large $m_{H^\pm} - m_{H^0}$)are discarded by perturbative limits.

Signal :: $\mathrm{p\ p} \rightarrow \mathrm{H}^+\ \mathrm{H}^-, (\mathrm{H}^- \rightarrow \ell^-\ \overline{\nu_\ell}\ \mathrm{H}^0), (\mathrm{H}^+ \rightarrow \ell^+\ \nu_\ell\ \mathrm{H}^0) \quad \ell = \mathrm{e}, \mu$

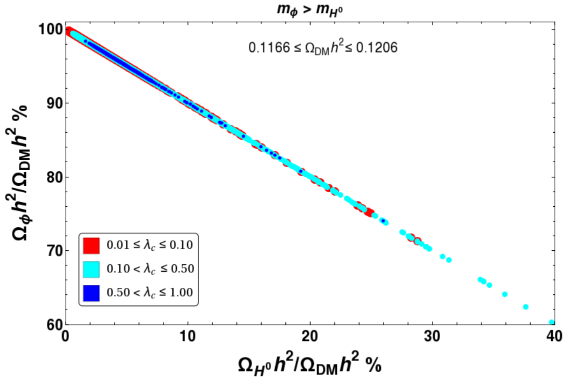
- $m_{H^\pm} - m_{H^0} > m_{W^\pm}$





BPs	$m_{H^\pm} - m_{H^0}$	$\{\lambda_1, \lambda_2, \lambda_3\}$	$\{M_R, \mathrm{Tr}[Y_\nu^\dagger Y_\nu]\}$	Validity Scale (μ)
BPD1	106 ($> m_W$)	$\{1.024, -0.7588, -0.2571\}$	$\{10^8, 0.5\}$	10^{10}
BPD2	143 ($> m_W$)	$\{1.538, -1.354, -0.1718\}$	$\{10^6, 0.5\}$	10^8

- The presence of DM-DM interactions enlarge the available parameter space significantly (by reviving the below 500GeV mass region for both the DM candidates).
- At the same time absolute EW vacuum can be achieved even in presence neutrinos.
- The inert scalar doublet DM can also produce leptonic collider signature at LHC.



$m_\phi > m_{H^0}$
$0.1166 \le \Omega_{DM}h^2 \le 0.1206$
$0.01 \le \lambda_c \le 0.10$
$0.10 < \lambda_c \le 0.50$
$0.50 < \lambda_c \le 1.00$
$\Omega_\phi h^2/\Omega_{DM}h^2$ %
$\Omega_{H^0}h^2/\Omega_{DM}h^2$ %

In oder to get the potential bounded from below, the quartic couplings of the potential (H, Φ, ϕ) must have to satisfy following co-positivity conditions following ,

$$\begin{aligned}
\mathrm{CPC}\{1,2,3\} : \lambda_{\mathrm{H}}(\mu) \geq 0, \quad \lambda_{\Phi}(\mu) \geq 0, \quad \lambda_{\phi}(\mu) \geq 0, \\
\mathrm{CPC}\{4,5\} : \Big(\lambda_1(\mu) + \lambda_2(\mu) \pm \lambda_3(\mu)\Big) + \sqrt{\lambda_{\mathrm{H}}(\mu)\lambda_{\Phi}(\mu)} \geq 0, \\
\mathrm{CPC}\{6,7\} : \lambda_1(\mu) + 2\sqrt{\lambda_{\mathrm{H}}(\mu)\lambda_{\Phi}(\mu)} \geq 0, \quad \lambda_{\phi\mathrm{h}}(\mu) + \sqrt{\frac{2}{3}\lambda_{\mathrm{H}}(\mu)\lambda_{\Phi}(\mu)} \geq 0, \\
\mathrm{CPC8} : \lambda_{\mathrm{c}}(\mu) + \sqrt{\frac{2}{3}\lambda_{\Phi}(\mu)\lambda_{\phi}(\mu)} \geq 0 \ ,
\end{aligned} \tag{1}$$

Next we turn to the constraints imposed by tree level unitarity of the theory, coming from all possible $2 \to 2$ scattering amplitudes as follows as :

$$\begin{aligned} |\lambda_H| < 4\pi, \quad |\lambda_\Phi| < 4\pi, \\ |\lambda_c| < 8\pi, \quad |\lambda_{\phi h}| < 8\pi, \\ |\lambda_1| < 8\pi, \quad |\lambda_1 + 2(\lambda_2 + \lambda_3)| < 8\pi \\ |\lambda_1 + \lambda_2 + \lambda_3| < 8\pi, \ \ |\lambda_1 - \lambda_2 - \lambda_3| < 8\pi, \\ |(\lambda_\Phi + \lambda_H) \pm \sqrt{(\lambda_2 + \lambda_3)^2 + (\lambda_H - \lambda_\Phi)^2}| < 8\pi, \\ \text{and} \quad |x_{1,2,3}| < 16\pi \ . \end{aligned}$$

where $x_{1,2,3}$ be the roots of the following cubic equation

$$\begin{aligned} & x^3 + x^2(-12\lambda_H - 12\lambda_\Phi - \lambda_\phi) + x(-16\lambda_1^2 - 16\lambda_1\lambda_2 - 16\lambda_1\lambda_3 - 4\lambda_2^2 - 8\lambda_2\lambda_3 - 4\lambda_3^2 - 4\lambda_c^2 \\ & \quad + 144\lambda_H\lambda_\Phi + 12\lambda_H\lambda_\phi + 12\lambda_\Phi\lambda_\phi - 4\lambda_{\phi h}^2) + 16\lambda_1^2\lambda_\phi + 16\lambda_1\lambda_2\lambda_\phi + 16\lambda_1\lambda_3\lambda_\phi - 32\lambda_1\lambda_c\lambda_{\phi h} \\ & \quad + 4\lambda_2^2\lambda_\phi + 8\lambda_2\lambda_3\lambda_\phi - 16\lambda_2\lambda_c\lambda_{\phi h} + 4\lambda_3^2\lambda_\phi - 16\lambda_3\lambda_c\lambda_{\phi h} + 48\lambda_c^2\lambda_H - 144\lambda_H\lambda_\Phi\lambda_\phi + 48\lambda_\Phi\lambda_{\phi h}^2 \\ & \quad = 0 \end{aligned}$$

RG Running

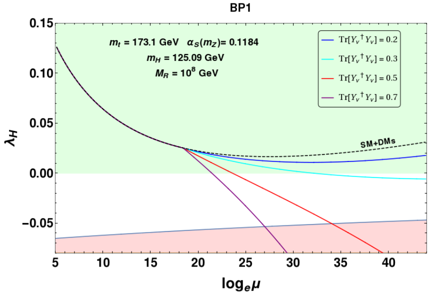
- Step I: $m_t \rightarrow \mathrm{M_R}$

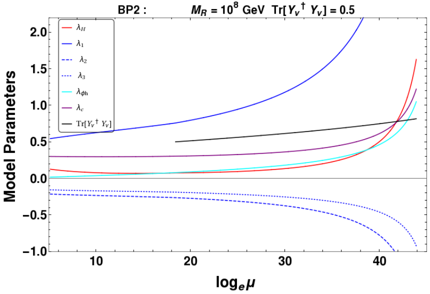
$$\beta_c = \beta_c^{SM} + \beta_c^{\Phi} + \beta_c^{\phi}$$

- Step II:
  $M_R \rightarrow \mu(> \mathrm{M_R})$

$$\beta_c = \beta_c^{SM} + \beta_c^{\Phi} + \beta_c^{\phi} + \beta_c^{\nu}$$

1. Check Stability : $\lambda_H(\mu) > 0$
2. Perturbativity at $\mu(> M_R)$:
   $\lambda_i(\mu) \leq 4\pi$, $|y_t(\mu)| \leq \sqrt{4\pi}$
   $|g_i| \leq \sqrt{4\pi}$, $\mathrm{Tr}[Y_\nu^\dagger Y_\nu] \leq 4\pi$.
3. Unitarity $|\mathcal{M}^{2\rightarrow 2}| < 8\pi$
4. Co-positivity conditions





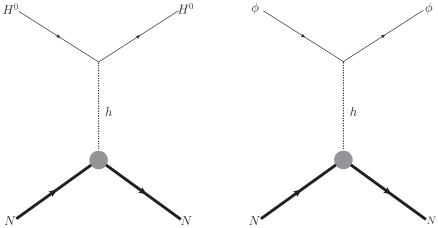


Figure 1: Spin independent direct detection processes for IDM (left) and scalar singlet DM (right).

The SI DD cross section for H^0 (σ_{H^0}) and for ϕ (σ_ϕ) at tree level turn out to be :

$$\sigma_{H^0}^{\text{eff, tree}} = \left(\frac{\Omega_H}{\Omega_{\rm DM}}\right)\frac{\lambda_L^2 f_N^2}{\pi}\frac{\mu_{H^0,N}^2 m_N^2}{m_h^4 m_{H_0}^2}, \quad \sigma_{\phi}^{\text{eff, tree}} = \left(\frac{\Omega_\phi}{\Omega_{\rm DM}}\right)\frac{\lambda_{\phi h}^2 f_N^2}{4\pi}\frac{\mu_{\phi,N}^2 m_N^2}{m_h^4 m_{\phi}^2},$$

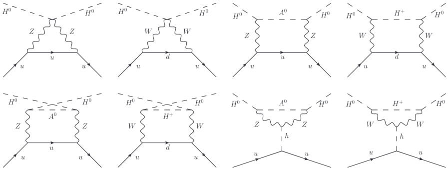
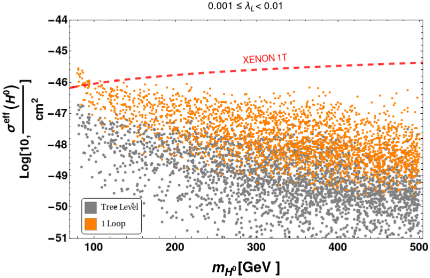


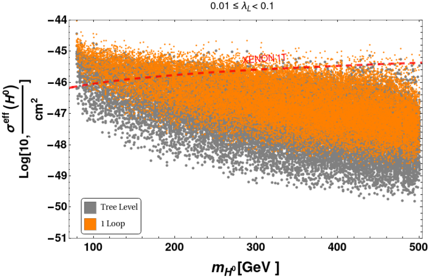
Figure 1: *The Feynman diagrams that give the dominant corrections to the direct detection cross section of inert higgs dark matter.*

In presence of loop effects, the coupling (λ_L) that enters into $\sigma^{\rm eff}_{H^0}$ gets replaced by $\lambda_L^{\rm eff} = \lambda_L + \delta\lambda_L$ where $\delta\lambda_L$ takes into account the loop contributions effectively. Following this, we rewrite $\sigma^{\rm eff}_{H^0}$ as

$$\sigma^{\rm eff,\ 1\ loop}_{H^0} = \sigma^{\rm eff,\ tree}_{H^0}(1+\kappa),$$

Ref. arXiv:1302.1657


0.001 ≤ λ_L < 0.01
XENON 1T
Tree Level
1 Loop
Log[10, σ^eff (H^0) / cm^2]
m_{H^0} [GeV]
-44
-45
-46
-47
-48
-49
-50
-51
100
200
300
400
500


0.01 ≤ λ_L < 0.1
XENON 1T
Tree Level
1 Loop
Log[10, σ^eff (H^0) / cm^2]
m_{H^0} [GeV]
-44
-45
-46
-47
-48
-49
-50
-51
100
200
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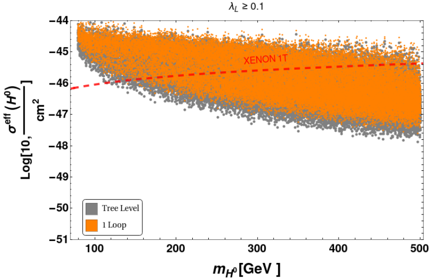
λ_L ≥ 0.1
XENON 1T
Tree Level
1 Loop
Log[10, σ^eff (H^0) / cm^2]
m_{H^0} [GeV]
-44
-45
-46
-47
-48
-49
-50
-51
100
200
300
400
500

$$
\begin{aligned}
\frac{dY_{N_i}}{dx} &= -0.264 M_{Pl}\sqrt{g}_* \frac{\mu}{x^2}\Bigg[\sum_j \Bigg\{\langle\sigma v_{\overline{N_i}N_j\to SM}\rangle\Big(Y_{N_i}Y_{N_j} - Y_{N_i}^{EQ}Y_{N_j}^{EQ}\Big) \\
&+\langle\sigma v_{\overline{N_i}N_j\to SS}\rangle\Big(Y_{N_i}Y_{N_j} - \frac{Y_{N_i}^{EQ}Y_{N_j}^{EQ}}{{Y_S^{EQ}}^2}Y_S^2\Big)\Theta(m_{N_i}+m_{N_j}-2m_S) \\
&-\langle\sigma v_{SS\to\overline{N_i}N_j}\rangle\Big(Y_S^2 - \frac{{Y_S^{EQ}}^2}{Y_{N_i}^{EQ}Y_{N_j}^{EQ}}Y_{N_i}Y_{N_j}\Big)\Theta(2m_S - m_{N_i} - m_{N_j})\Bigg\} \\
&+\langle\sigma v_{\overline{N_i}N^\pm\to SM}\rangle\Big(Y_{N_i}Y_{N^\pm} - Y_{N_i}^{EQ}Y_{N^\pm}^{EQ}\Big)\Bigg], \\
\frac{dY_S}{dx} &= -0.264 M_{Pl}\sqrt{g}_* \frac{\mu}{x^2}\Bigg[\langle\sigma v_{SS\to SM}\rangle\Big({Y_S}^2 - {Y_S^{EQ}}^2\Big) \\
&+\sum_{i,j}\Bigg\{-\langle\sigma v_{\overline{N_i}N_j\to SS}\rangle\Big(Y_{N_i}Y_{N_j} - \frac{Y_{N_i}^{EQ}Y_{N_j}^{EQ}}{{Y_S^{EQ}}^2}Y_S^2\Big)\Theta(m_{N_i}+m_{N_j}-2m_S) \\
&+\langle\sigma v_{SS\to\overline{N_i}N_j}\rangle\Big(Y_S^2 - \frac{{Y_S^{EQ}}^2}{Y_{N_i}^{EQ}Y_{N_j}^{EQ}}Y_{N_i}Y_{N_j}\Big)\Theta(2m_S - m_{N_i} - m_{N_j})\Bigg],
\end{aligned}
\tag{2}
$$

$$
\begin{aligned}
R &= n_t \langle v \rangle n_\phi \sigma^{DD} \\
&= \left(\frac{n_t \langle v \rangle \rho_c}{m_\phi} \right) \Omega_\phi \sigma^{DD} \; .
\end{aligned}
$$

where $n_t = \frac{N}{A}$ with N is Avogadro number and A is atomic mass of the target. Then for the two component case:

$$
\begin{aligned}
R = \left(\frac{n_t \langle v \rangle \rho_c}{m_\phi} \right) \Omega_T \sigma_T^{SI} &= \left(\frac{n_t \langle v \rangle \rho_c}{m_{\phi_1}} \right) \Omega_1 \sigma_1^{DD} + \left(\frac{n_t \langle v \rangle \rho_c}{m_{\phi_2}} \right) \Omega_2 \sigma_2^{DD} \; , \\
&= \left(\frac{n_t \langle v \rangle \rho_c}{m_{\phi_1}} \right) [\Omega_1 \sigma_1^{DD} + \frac{m_{\phi_1}}{m_{\phi_2}} \Omega_2 \sigma_2^{DD}] \\
\therefore \qquad & \sigma_T^{SI} = \frac{\Omega_1}{\Omega_T} \sigma_1^{DD} + \frac{\Omega_2}{\Omega_T} \left(\frac{m_{\phi_1}}{m_{\phi_2}} \right) \sigma_2^{DD} \; .
\end{aligned}
$$