

# PHENOMENOLOGY OF DARK MATTER IN TWO HIGGS DOUBLET AND COMPLEX SINGLET MODEL

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# Introduction

- We explore models with two higgs doublet and extra complex singlet scalar as dark matter (DM) candidate (THDM-CS).
- Such a model is motivated from baryogenesis, gravitational waves, dark matter and inflation.
- The DM candidate interacts with the SM particles only via the higgses.

# The Model

- We consider a softly broken  $Z_2$  symmetric two higgs doublet model (THDM) extended with a complex singlet scalar ( $S$ ) as the dark matter (DM) candidate stabilised under  $Z_2'$ .
- The quantum numbers of the fields are

Particles	$Z_2$	$Z_2'$
$\Phi_1$	+1	+1
$\Phi_2$	-1	+1
$S$	+1	-1

**Table:** The quantum numbers of the Higgs doublets  $\Phi_1, \Phi_2$  and complex singlet  $S$  under  $Z_2 \times Z_2'$ .

# The Scalar Potential

$$\mathcal{V}_{THDMCS} = \mathcal{V}_{THDM} + \mathcal{V}_S + \mathcal{V}_{HS}$$

$$\mathcal{V}_{THDM} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + (\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + h.c.)$$

$$\mathcal{V}_S = m_S^2 S^\dagger S + (\frac{m_{S'}^2}{2} S^2 + h.c.) + (\frac{\lambda_1''}{24} S^4 + h.c.) + \frac{\lambda_1''}{6} (S^2 (S^\dagger S) + h.c.) + \frac{\lambda_3''}{4} (S^\dagger S)^2$$

$$\mathcal{V}_{HS} = [S^\dagger S (\lambda_1' \Phi_1^\dagger \Phi_1 + \lambda_2' \Phi_2^\dagger \Phi_2)] + [S^2 (\lambda_4' \Phi_1^\dagger \Phi_1 + \lambda_5' \Phi_2^\dagger \Phi_2) + h.c.]$$

(Baum, Shah JHEP 12 (044) 2018)

- The higgs sector for the CP-conserving THDM-CS is the same as the THDM and consists of  $h, H, A, H^\pm$  where  $h, H$  are the CP-even scalars,  $A$  is the pseudoscalar and  $H^\pm$ , the charged higgses.
- 16 free parameters in the model

$$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m_{12}^2, \alpha, \tan \beta, \lambda'_1, \lambda'_2, \lambda'_4, \lambda'_5, \lambda''_1, \lambda''_3, m_S^2, m_{S'}$$

# Phenomenological constraints

- Relic density upper bound from Planck.
- Spin-independent DM-nucleon direct detection cross section from XENON-1T.
- Lightest CP-even Higgs mass 125 GeV
- Collider limits on heavy higgses from LHC and LEP
- Flavour physics constraints:  $\text{BR}(B \rightarrow s\gamma)$ ,  $\text{BR}(B \rightarrow \mu^+\mu^-)$

# Simulation details

Model implementation/adoption in the following codes:

- Model building: SARAH
- Spectrum Generator: SARAH-SPheno
- DM constraints: micrOMEGAs
- Higgs constraints: HiggsBounds and HiggsSignals
- Flavour constraints and tree-level unitarity constraints: SPheno

# Benchmark scenario

Parameters	BP1
$m_{12}^2$	$-1.014 \times 10^5$
$\lambda_1$	0.233
$\lambda_2$	0.249
$\lambda_3$	0.389
$\lambda_4$	-0.167
$\lambda_5$	0.001
$\lambda_1''$	0.1
$\lambda_3''$	0.1
$\lambda_1'$	0.04
$\lambda_2'$	0.04
$\lambda_4'$	0.1
$\lambda_5'$	0.1
$m_h$	125.1
$m_H$	724.4
$m_A$	724.4
$m_{H^\pm}$	728.3
$\tan \beta$	5
$m_\chi$	338.9
$\Omega h^2$	0.059
$\sigma_{SI}^n \times 10^{11}$ (pb)	7.55

Table: Relevant parameters of the benchmark used for the study



# Some favourable regions of the parameter space: Relic Density

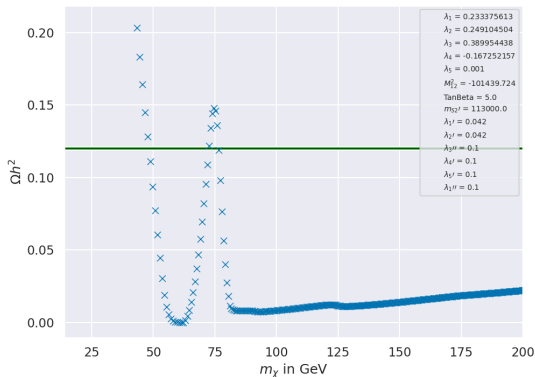
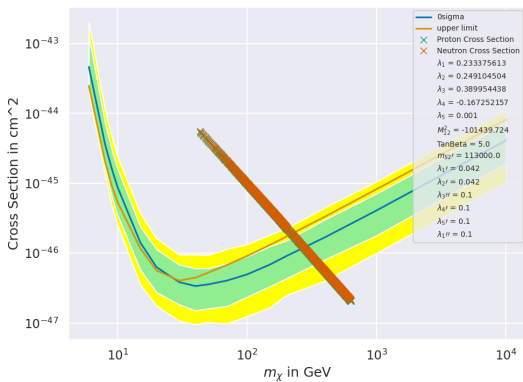


Figure: Variation of the relic density with the mass of the DM candidate,  $m_\chi$ . Here, the mass parameter  $m_{32}^1$  is varied.

# Spin-independent direct detection cross section



**Figure:** Variation of the spin-independent direct detection cross section with the mass of the DM candidate,  $m_{\chi}$  and compared to the limits from XENON-1T. Here, the mass parameter  $m_{\chi^2}$  is varied.

## Variation of other parameters

- Some relevant couplings of the higgs to the DM candidate are:

$$\lambda_{hSS} = \lambda_{hS^*S^*} = 2i \frac{v}{\sqrt{1+\tan^2\beta}} (\lambda'_4 \sin\alpha - \lambda'_5 \tan\beta \cos\alpha)$$

$$\lambda_{hSS^*} = i \frac{v}{\sqrt{1+\tan^2\beta}} (\lambda'_1 \sin\alpha - \lambda'_2 \tan\beta \cos\alpha)$$

where  $\alpha$  is the mixing angle in the CP-even higgs sector and  $\tan\beta = \frac{v_2}{v_1}$  where  $v_1$  and  $v_2$  are the vacuum expectation value's of  $\Phi_1$  and  $\Phi_2$  respectively.

- We now vary the other parameters in the scalar potential for the singlet:  $\lambda'_1, \lambda'_2, \lambda'_4, \lambda'_5$  and  $\tan\beta$  individually.

# Variation of direct detection cross section with $\lambda'_2$

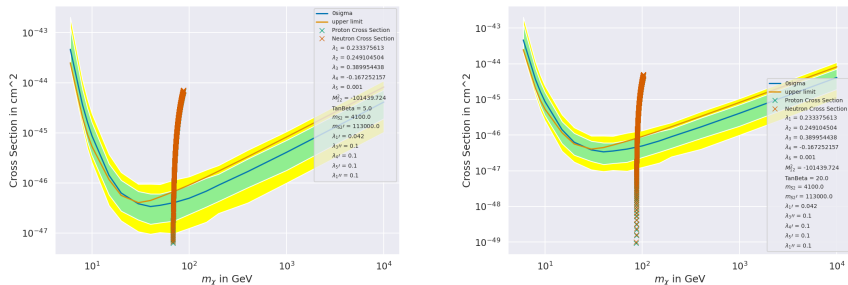


Figure: Variation of the direct detection cross section with mass of the DM,  $m_\chi$  for varying  $\lambda'_2$  for two values of  $\tan\beta = 5, 20$  (left, right).

- so far observed strongest effect on the cross section via  $\lambda'_2$ .
- low  $\lambda'_2$  favoured for agreement with direct detection limits

# Variation of relic density on $\tan \beta$

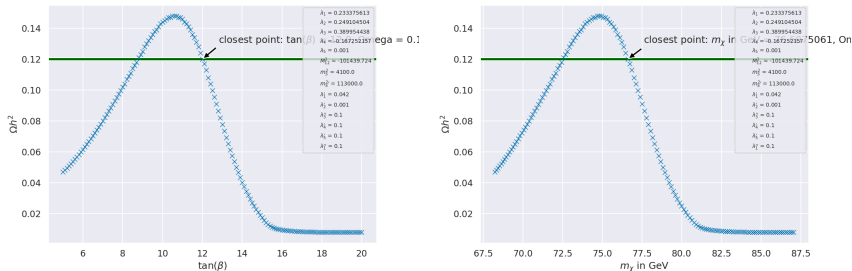


Figure: Variation of relic density with  $\tan \beta$  (left) and mass of the DM,  $m_\chi$  (right) for  $\lambda'_2 = 0.001$ .

Benchmark point with DM mass,  $m_\chi \simeq 77$  GeV satisfies both thermal relic and direct detection cross section.

# Summary

- Extensions of THDM with complex scalar singlet provide a potential DM candidate.
- We study the possibility of obtaining suitable parameter points satisfying DM constraints and accomodating a light 125 GeV Higgs
- Possibility of light and heavy DM, for e.g,  $\simeq 77$  GeV and  $\sim 339$  GeV respectively.

## Ongoing work

- Comparison with other existing DM code `madDM`.
- Constraints from the Higgs signal strengths in the light DM mass range.
- Collider phenomenology on model determination and distinction → LHC, LC, and beyond.

Thank you !