

# Higgs Portal Inflation with Fermionic Dark Matter

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**Abstract.** We discuss the inflationary model presented in [1], involving a gauge singlet scalar field and fermionic dark matter added to the standard model. Either the Higgs or the singlet scalar could play the role of the inflaton, and slow roll is realized through its non-minimal coupling to gravity. The effective scalar potential is stabilized by the mixing between the scalars as well as the coupling with the fermionic field. Mixing of the two scalars also provides a portal to dark matter. Constraints on the model come from perturbativity and stability, collider searches and dark matter constraints and impose a constraining relationship on the masses of dark matter and scalar fields. Inflationary predictions are generically consistent with current Planck data.

## 1 Introduction

The paradigm of cosmic inflation is currently very well established as a possible description of the early history of the observable universe. It is interesting from both the quantum gravity as well as the particle phenomenology viewpoints. While the simplest inflationary scenarios such as single field slow roll (SFSR) inflation, where exponential expansion of the universe is driven by the potential energy of a slowly rolling scalar (inflaton) field, are still consistent with observations, the picture remains unsatisfactory due to the lack of knowledge about the nature of the inflaton field and its connection with the familiar standard model fields.

A few years ago it was shown [2] that the standard model Higgs (with nonminimal coupling to gravity) could play the role of the inflaton field. While the idea is very attractive, it has been observed that the model may be unviable due to the instability of the Higgs potential after accounting for loop corrections [3]. Without accounting for new physics, the only way to avoid this is by assuming a top quark pole mass about  $3\sigma$  below its central value [4]. Even after doing this, inflationary predictions could still be highly sensitive to the exact values of parameters [5].

In the present work we describe our model introduced in [1] that attempts to address the Higgs instability problem by adding two new fields to the standard model. The model aims to enable inflation to proceed successfully and also provide a plausible dark matter candidate.

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## 2 Model Description

The model consists of two fields in addition to the standard model field content: a gauge singlet scalar  $S$  which couples to the Higgs, and a gauge singlet fermion  $\psi$  which plays the role of dark matter. We introduce a  $Z_2$  symmetry under which  $S$  and one of the Weyl components of  $\psi$  (which we call  $\psi_1$ ) are odd, while the other Weyl component ( $\psi_2$ ) and all the standard model fields are even. Both scalar fields can be nonminimally coupled to gravity.

The Jordan frame Lagrangian is

$$\mathcal{L} = \sqrt{-g} \left[ -\frac{M_{\text{pl}}^2 + 2\xi_h H^\dagger H + \xi_s S^2}{2} R + \partial_\mu H^\dagger \partial^\mu H + \frac{1}{2} (\partial_\mu S)^2 - V(H, S) + \mathcal{L}_{\text{DM}} \right], \quad (1)$$

where  $M_{\text{pl}}$  is the reduced Planck mass and  $H = \begin{pmatrix} \pi^+ \\ \frac{1}{\sqrt{2}} (\phi + i\pi^0) \end{pmatrix}$  is the Higgs doublet. The two-field scalar potential and dark matter lagrangian are defined as follows:

$$V(H, S) = -\mu_h^2 H^\dagger H + \lambda_h (H^\dagger H)^2 - \frac{1}{2} \mu_s^2 S^2 + \frac{1}{4} \lambda_s S^4 + \frac{1}{2} \lambda_{sh} H^\dagger H S^2 + \kappa S, \quad (2)$$

$$\mathcal{L}_{\text{DM}} = i\bar{\psi}\gamma^\mu \partial_\mu \psi - y_\psi S \bar{\psi}\psi. \quad (3)$$

The soft breaking term  $\kappa S$  (ignored from here on) raises the degeneracy of the  $Z_2$  symmetry thus helping to avoid the domain wall problem.

After symmetry breaking, in general, both  $S$  and  $\phi$  (the neutral component of the Higgs doublet  $H$ ) in the tree-level potential develop vacuum expectation values. The values of these fields in the electroweak minimum can be denoted as

$$v \equiv \langle \phi \rangle, \quad u \equiv \langle S \rangle. \quad (4)$$

The mass matrix of the two scalars can be written as

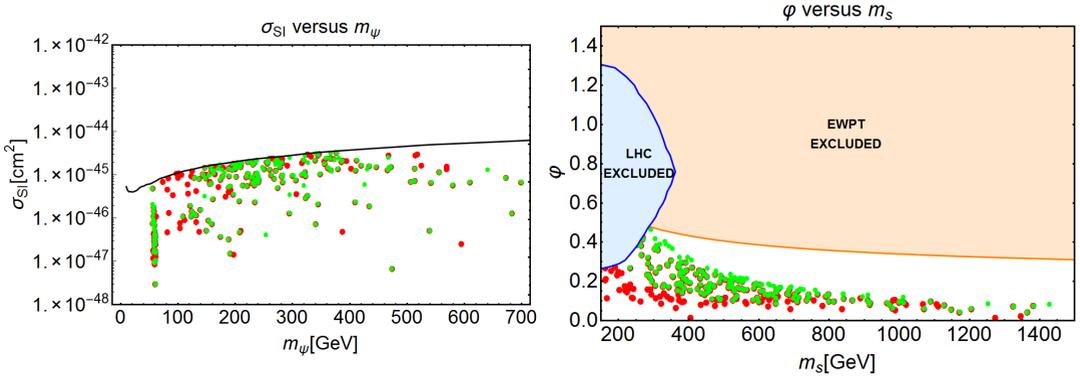
$$\mathcal{M}_{\text{scalar}}^2(\phi, S) \equiv \begin{pmatrix} m_{\phi\phi}^2 & m_{s\phi}^2 \\ m_{s\phi}^2 & m_{ss}^2 \end{pmatrix}, \quad (5)$$

which on diagonalizing gives us the mixing angle  $\varphi$  between the two scalars whose present day value is given by

$$\varphi = \frac{1}{2} \arctan \frac{\lambda_{sh} v u}{\lambda_s u^2 - \lambda_h v^2} \quad (6)$$

## 3 Constraints

We consider three types of constraints that the model needs to satisfy in the interest of self-consistency and agreement with observations. These constraints are discussed in the following subsections.



**Figure 1.** The figure on the left shows the spin independent direct detection cross section  $\sigma_{SI}$  plotted as a function of dark matter mass. The black line here corresponds to the LUX bound. The figure on the right shows mixing angle  $\phi$  as a function of mass of the scalar field at its low energy vacuum,  $m_s$ . The orange line corresponds to the EWPT upper bound on  $\phi$  and the blue line corresponds to LHC physics lower bound on  $m_s$ . The orange and blue shaded regions are excluded by these bounds respectively. In both figures, the green and red points correspond to  $h$ -inflation and  $s$ -inflation respectively. Both figures are from [1].

### 3.1 Inflation Constraints

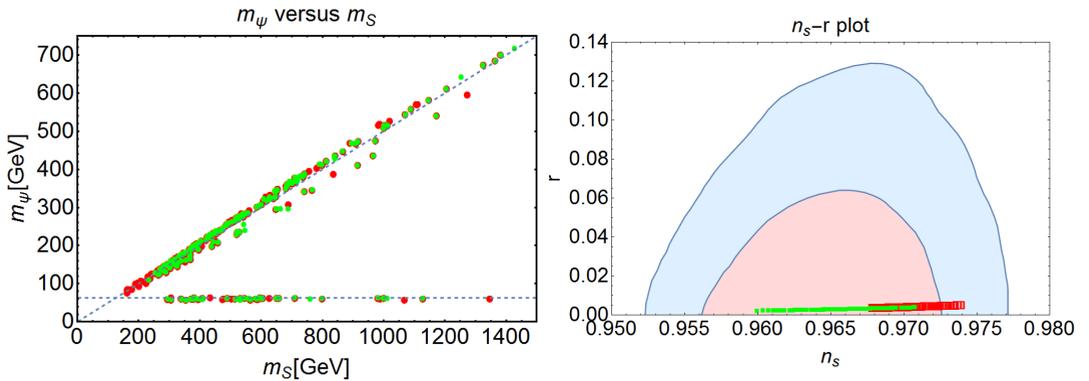
In this model, slow-roll inflation can happen either along the  $\phi$ -axis ( $h$ -inflation) or the  $S$ -axis ( $s$ -inflation), which means that either  $\phi$  or  $S$  would take large field values (typically  $O(10^{16}$  GeV) or higher). The mechanism of inflation is very similar to the standard Higgs inflation scenario [2], with a large non-minimal coupling of the inflaton helping to flatten the Einstein-frame potential at large field values. For ease of analysis, the nonminimal coupling of the other field is taken to be small ( $O(1)$ ).

The loop corrected inflaton potential can be obtained after accounting for the running of the various couplings, especially the self-coupling of the inflaton field. For the model to be consistent, the couplings should remain perturbative at all scales, starting from their electroweak scale values (relevant for late-time physics) all the way up to inflationary scale. Moreover, the potential obtained in this manner must be positive all through the relevant scales and sloping in the correct direction so that the inflaton is likely to eventually settle at the electroweak minimum. Additionally, the inflationary axis must always be a valley and the mass-squared in the transverse direction must be positive and sufficiently large ( $m_T^2 \gg H^2$  to avoid isocurvature perturbations).

These conditions impose various constraints on the starting (near electroweak scale) values of the various couplings such as  $y_\psi$ ,  $\lambda_s$ ,  $\lambda_{sh}$ , etc., most notably imposing an upper bound on all of their values and constraining  $\lambda_{sh}$  to be positive. The range of values of couplings that produce satisfactory running behaviour can be further tested against other constraints coming from dark matter physics and collider phenomenology.

### 3.2 Dark Matter Constraints

At the end of inflation, the potential energy of the inflaton is converted into kinetic energy and eventually transferred into excitations of the various standard model fields. A detailed analysis of this kind was done in the context of standard Higgs inflation in [6]. We expect a similar process (corrected for the existence of  $S$  and  $\psi$  fields) to occur for our model for typical values of input parameters. As



**Figure 2.** In the figure on the left, dark matter mass  $m_\psi$  is plotted against the scalar mass  $m_s$ . The dashed lines correspond to  $m_\psi = (1/2)m_s$  and  $m_\psi = (1/2)m_h$  respectively. In the figure on the right,  $n_s$ – $r$  values for  $h$ –inflation and  $s$ –inflation are shown with allowed region from Planck 2015 [12] shown in the background. In both figures, the green and red points correspond to  $h$ –inflation and  $s$ –inflation respectively. Both figures are from [1].

long as the Yukawa coupling  $y_\psi$  and the mixing angle  $\varphi$  are not unnaturally small, we expect dark matter production to follow the usual WIMP scenario. Therefore, the relic abundance of dark matter can be calculated by computing dark matter interaction cross sections from the values of the various couplings. The obtained relic density is then compared to the Planck 2015 TT,TE,EE+lowP data  $\Omega_c h^2 = 0.1198 \pm 0.0015$  [7] to obtain an additional constraint on the model parameter space.

Apart from producing the correct relic density of dark matter, the model should also satisfy the constraints on dark matter interaction with the standard model imposed by the direct detection experiments. The spin-independent cross section of dark matter for successful data points is compared to the LUX bounds [8] in the first plot in Figure 1.

### 3.3 Collider Constraints

Collider constraints for the model primarily arise from the fact that there is a mixing between the Higgs and the  $S$  fields. The mixing is parametrized by the mixing angle  $\varphi$ , which is therefore constrained by collider experiments. We consider constraints coming from Electroweak Precision Tests (EWPT) [9] and also constraints from LHC [10] translated into a constraint in the  $m_s - \varphi$  plane in [11]. The constraints are shown in the second plot in Figure 1.

## 4 Results and Conclusions

The first plot in Figure 2 shows dark matter mass  $m_\psi$  as a function of scalar mass  $m_s$ , for data points which successfully pass all the constraints. It is clear that the dark matter mass ( $m_\psi$ ) tends to take values corresponding to the resonance regions, i.e., nearly half the scalar mass ( $m_s$ ) or half the Higgs mass ( $m_h$ ). This is chiefly a consequence of combining the upper bounds on the couplings coming from requiring appropriate running behaviour with the constraints coming from relic density and direct detection.

The second plot in Figure 2 gives the  $n_s - r$  predictions from the model. It is clear that the inflationary predictions of  $h$ – and  $s$ –inflation are not markedly different. This is not surprising since at inflationary scales, both types of inflation involve a scalar field with nearly quartic potential and

quadratic nonminimal coupling to gravity, with some modifications coming from the exact running behaviour of the couplings. It is also clear that the model generically predicts a low tensor to scalar ratio, similar to standard (tree level) Higgs inflation and therefore the predictions are generally well within the Planck-selected region.

The original motivation of the paper was to come up with a model that would address the potential instability of the Higgs field and enable to have inflation. An additional objective was to explore the possibility of connecting dark matter physics with inflation. In this model involving adding a gauge singlet scalar and singlet fermionic dark matter to the standard model, both objectives could be achieved, albeit in a limited region of parameter space where dark matter mass is nearly half the mass of one of the scalars (resonance regions). It was discovered that inflation could be achieved along either axis and will generically yield low tensor-to-scalar ratio ( $r$ ) and a relatively large spread of scalar spectral tilt ( $n_s$ ) that could still lie within the Planck-allowed region.

In the coming years, we expect to have more restrictive constraints from dark matter direct detection and colliders. Therefore, there is promise that the model parameter space may be further constrained. Moreover, upcoming CMB B-mode searches are expected to detect or further constrain the tensor-to-scalar ratio, which could improve the distinguishing power between various inflationary models and also potentially verify the inflationary predictions of this model.

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## References

- [1] A. Aravind, M. Xiao and J. H. Yu, *Phys. Rev. D* **93**, no. 12, 123513 (2016) doi:10.1103/PhysRevD.93.123513 [arXiv:1512.09126 [hep-ph]].
- [2] F. L. Bezrukov and M. Shaposhnikov, *Phys. Lett. B* **659**, 703 (2008) doi:10.1016/j.physletb.2007.11.072 [arXiv:0710.3755 [hep-th]].
- [3] G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori and A. Strumia, *JHEP* **1208**, 098 (2012) doi:10.1007/JHEP08(2012)098 [arXiv:1205.6497 [hep-ph]].
- [4] A. Salvio, *Phys. Lett. B* **727**, 234 (2013) doi:10.1016/j.physletb.2013.10.042 [arXiv:1308.2244 [hep-ph]].
- [5] K. Allison, *JHEP* **1402**, 040 (2014) doi:10.1007/JHEP02(2014)040 [arXiv:1306.6931 [hep-ph]].
- [6] F. Bezrukov, D. Gorbunov and M. Shaposhnikov, *JCAP* **0906**, 029 (2009) doi:10.1088/1475-7516/2009/06/029 [arXiv:0812.3622 [hep-ph]].
- [7] P. A. R. Ade *et al.* [Planck Collaboration], arXiv:1502.01589 [astro-ph.CO].
- [8] D. S. Akerib *et al.* [LUX Collaboration], arXiv:1512.03506 [astro-ph.CO].
- [9] S. Baek, P. Ko, W. I. Park and E. Senaha, *JHEP* **1211**, 116 (2012) doi:10.1007/JHEP11(2012)116 [arXiv:1209.4163 [hep-ph]].
- [10] S. Chatrchyan *et al.* [CMS Collaboration], *Eur. Phys. J. C* **73**, 2469 (2013) doi:10.1140/epjc/s10052-013-2469-8 [arXiv:1304.0213 [hep-ex]].
- [11] M. L. Xiao and J. H. Yu, *Phys. Rev. D* **90**, no. 1, 014007 (2014) Addendum: [*Phys. Rev. D* **90**, no. 1, 019901 (2014)] doi:10.1103/PhysRevD.90.014007, 10.1103/PhysRevD.90.019901 [arXiv:1404.0681 [hep-ph]].
- [12] P. A. R. Ade *et al.* [Planck Collaboration], [arXiv:1502.02114 [astro-ph.CO]].