Higgs-Portal Inflation in a DFSZ Axion-model

2HDM Working Group

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Overview

1. The DFSZ Axion model dubbed 2hdSMASH
2. Higgs-Inflation in 2hdSMASH
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The DFSZ Axion model dubbed 2hdSMASH

- 2hdSMASH: 2HD-SM-Axion-Seesaw-Higgs Portal Inflation
- It is based on a DFSZ Axion model: **2HDM Type** II **+ Complex Scalar Singlet +** ν_R with a global $\mathbf{U(1)_{PQ}}$**-Symmetry**
- Under $U(1)_{PQ}$-Symmetry, the scalar fields transform as:

$$\sigma \to \sigma \cdot \exp(i\alpha) \ , \ H_u \to H_u \cdot \exp(iX_u\alpha) \ , \ H_d \to H_d \cdot \exp(-iX_d\alpha) \qquad (1)$$

with PQ-charges $X_\sigma = 1$,X_u and X_d which satisfy $X_u + X_d = 2$

The DFSZ Axion model dubbed 2hdSMASH

> The most general DFSZ scalar potential under $U(1)_{PQ}$-Symmetry is given by:

$$\begin{aligned} V_J(H_u, H_d, \sigma) =& m_{uu}^2 |H_u|^2 + m_{dd}^2 |H_d|^2 + m_{\sigma\sigma}^2 |\sigma|^2 \\ &+ \frac{1}{2}\lambda_1 |H_u|^4 + \frac{1}{2}\lambda_2 |H_d|^4 + \lambda_3 |H_u|^2 |H_d|^2 + \lambda_4 \left(H_u^\dagger H_d\right)\left(H_d^\dagger H_u\right) \\ &+ \frac{1}{2}\lambda_\sigma |\sigma|^4 + \lambda_{1\sigma} |H_u|^2 |\sigma|^2 + \lambda_{2\sigma} |H_d|^2 |\sigma|^2 - \epsilon\left(H_u^\dagger H_d \sigma^2 + H_d^\dagger H_u \sigma^{*2}\right) \end{aligned} \tag{2}$$

> Higgs-Portal Inflation given by non-minimal coupling ξ_i to gravity in Jordan frame:

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} \supset \left[\frac{M^2}{2} + \xi_u H_u^\dagger H_u + \xi_d H_d^\dagger H_d + \xi_\sigma \sigma^\dagger \sigma\right] R - V_J \tag{3}$$

with the reduced Planck mass $M_p^2 = M^2 + \xi_u v_u^2 + \xi_d v_d^2 + \xi_\sigma v_{PQ}^2 \overset{\text{set}}{\equiv} 1$

The DFSZ Axion model dubbed 2hdSMASH

> The metric transforms from Jordan frame to Einstein frame as:

$$g^E_{\mu\nu} = \Omega^2 g^J_{\mu\nu} \tag{4}$$

with Weyl transformation $\Omega^2 = 1 + 2\xi_u H_u^\dagger H_u + 2\xi_d H_d^\dagger H_d + 2\xi_\sigma \sigma^\dagger \sigma$

> Scalar potential in Einstein frame:

$$V_E = \frac{V_J}{\Omega^4} \tag{5}$$

The DFSZ Axion model dubbed 2hdSMASH

> The neutral field content under $U(1)_{PQ}$-Symmetry can be parametrized as:

$$H_u^0 = \frac{v_u + h_u}{\sqrt{2}} \cdot e^{-iA_u/v_u} \ , \ H_d^0 = \frac{v_u + h_u}{\sqrt{2}} \cdot e^{iA_d/v_d} \ , \ \sigma = \frac{v_{PQ} + \rho}{\sqrt{2}} \cdot e^{iA_\sigma/v_{PQ}} \tag{6}$$

with A_i the angular fields, v_{PQ} the PQ scale and ρ the saxion

> Thus, the quartic DFSZ scalar potential with non-minimal coupling reads:

$$V_4 = \frac{\lambda_1 h_u^4 + \lambda_2 h_d^4 + 2\lambda_{34} h_u^2 h_d^2 + \lambda_\sigma \rho^4 + 2\rho^2 \left(\lambda_{1\sigma} h_u^2 + \lambda_{2\sigma} h_d^2 - 2\epsilon h_u h_d \cos(2\Theta)\right)}{8\left(1 + \xi_u h_u^2 + \xi_d h_d^2 + \xi_\sigma \rho^2\right)^2} \tag{7}$$

Higgs Inflation in 2hdSMASH

- If we take $h_u \gg h_d, \rho$ we get:

$$V_{4,h_u} = \lim_{h_u \to \infty} V_4 = \frac{\lambda_1 h_u^4}{8\left(1+\xi_u h_u^2\right)^2} \overset{1 \ll \xi_u h_u^2}{\simeq} \frac{\lambda_1}{8\xi_u^2} \tag{8}$$

- The bounded from below condition and the condition for perturbative unitarity constrain λ_1:

$$0 < \lambda_1 < 4\pi \tag{9}$$

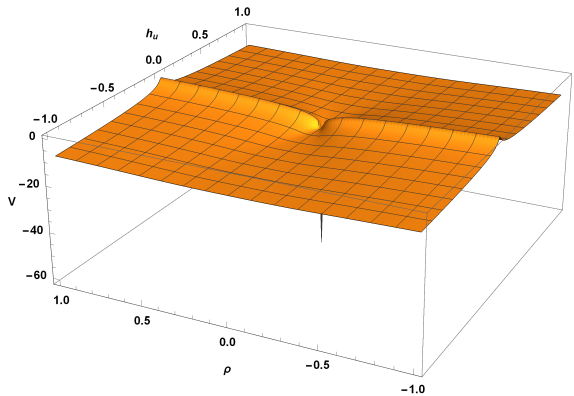
- Determining global minimum for successful inflation along h_u:

$$\frac{dV_4}{dh_u} = 0 \quad \text{and} \quad \left.\frac{d^2V_4}{(dh_u)^2}\right|_{h_u = h_u^0} > 0 \tag{10}$$

Higgs Inflation in 2hdSMASH

> The condition for a global minimum for the vaccum are given by:

$$\lambda_{34}\xi_u - \lambda_1\xi_d > 0\ ,\ \lambda_{34}\xi_d - \lambda_2\xi_u < 0\ ,\ \lambda_{1\sigma}\xi_u - \lambda_1\xi_\sigma > 0\ ,\ \lambda_{2\sigma}\xi_d - \lambda_2\xi_\sigma < 0 \qquad (11)$$



Higgs Inflation in 2hdSMASH

- Inflation along h_u can only occur if $\epsilon \simeq \left(\frac{V'(h_u)}{V(h_u)}\right)^2 \ll 1$
- Scalar perturbations along this path can be constrained by Cosmic Microwave Background observations $P_\zeta \propto \frac{V}{\epsilon} \simeq \frac{\lambda}{\xi^2} \sim 10^{-10}$
- The ratio $\lambda_1/\xi_u^2 \sim 10^{-10}$ for $\xi_u \sim 10^5$ and $\lambda_1 \sim \mathcal{O}(1)$
- Unitarity bound issue? $\longrightarrow$ Cutoff scale Λ_{Cutoff} is similar to the Inflationary scale Λ_I:

$$\Lambda_{\text{Cutoff}} \sim 1/\xi_u \sim \Lambda_I \tag{12}$$

Hidden-Scalar Inflation in 2hdSMASH

- If we take $\rho \gg h_u, h_d$ we get:

$$V_{4,\rho} = \lim_{\rho\to\infty} V_4 = \frac{\lambda_\sigma \rho^4}{8\left(1+\xi_\sigma\rho^2\right)^2} \overset{\xi_\sigma\rho^2\gg 1}{\simeq} \frac{\lambda_\sigma}{8\xi_\sigma^2} \tag{13}$$

- Boundedness from below and perturbative unitarity conditions:

$$0 < \lambda_\sigma < 4\pi \tag{14}$$

- Conditions for global minimum:

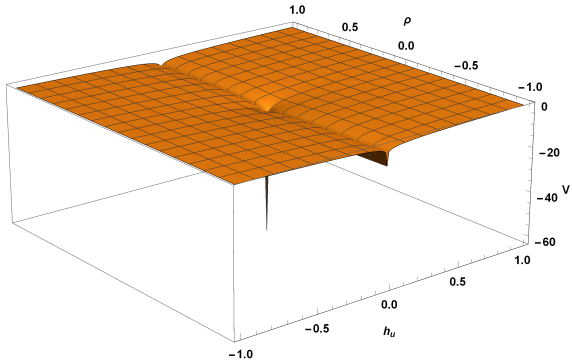
$$(\lambda_{1\sigma}\xi_\sigma - \lambda_\sigma\xi_1) > 0 \tag{15}$$

$$(\lambda_{2\sigma}\xi_\sigma - \lambda_\sigma\xi_2) > 0 \tag{16}$$

$$\frac{\xi_\sigma}{\lambda_\sigma}\left(\lambda_1\lambda_{2\sigma}\xi_d - \lambda_{34}(\lambda_{1\sigma}\xi_d + \lambda_{2\sigma}\xi_u) + \lambda_2\xi_u\lambda_{1\sigma} - 2\epsilon\sqrt{(\lambda_1\xi_d - \lambda_{34}\xi_u)(\lambda_2\xi_u - \lambda_{34}\xi_d)}\right)$$
$$> \lambda_1\xi_d^2 + \lambda_2\xi_u^2 - 2\lambda_{34}\xi_u\xi_d \tag{17}$$

Hidden-Scalar Inflation in 2hdSMASH

> λ_σ can be chosen to be $\sim 10^{-10} \rightarrow \xi_\sigma \sim 1$



Mixed-Higgs Inflation in 2hdSMASH

- Inflation along $h_u h_d$
- Parametrize neutral scalar field as follows:

$$h_u = h \sin\beta \ , \ h_d = h \cos\beta \ , \ \rho = r \sin\gamma \ , \ h = r \cos\gamma \tag{18}$$

with $h = \sqrt{h_u^2 + h_d^2}$ being the SM-like Higgs and $r = \sqrt{h^2 + \rho^2}$

- Taking $\gamma \to 0$ we get:

$$\lim_{\gamma \to 0} V_4 = V_{4,\text{2HDM}} \tag{19}$$

- Bounded from below condition and perturbative unitarity constraint:

$$\lambda_{34} + \sqrt{\lambda_1 \lambda_2} > 0 \ , \ 0 < \lambda_1 < 4\pi \ , \ 0 < \lambda_2 < 4\pi \tag{20}$$

Mixed-Higgs Inflation in 2hdSMASH

> Determining minimum for mixed-Higgs inflation:

$$\frac{dV_{4,\text{2HDM}}}{d\beta} = 0 \quad \text{and} \quad \left.\frac{d^2V_{4,\text{2HDM}}}{(d\beta)^2}\right|_{\beta=\beta^0} > 0 \tag{21}$$

> Inflationary direction:

$$\tan\beta_0 = \sqrt{\frac{\lambda_{34}\xi_u - \lambda_1\xi_d}{\lambda_{34}\xi_d - \lambda_2\xi_u}} \tag{22}$$

> Scalar potential:

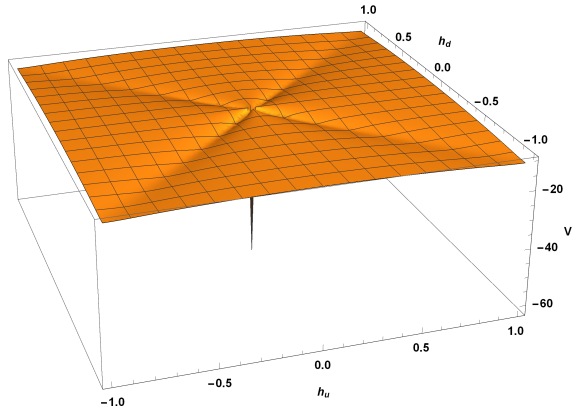
$$V_{4,\text{mixed Higgs}} = V_{4,\text{2HDM}}\big|_{\beta=\beta_0} \simeq \frac{\lambda_1\lambda_2 - \lambda_{34}^2}{8\left(\lambda_1\xi_d^2 + \lambda_2\xi_u^2 - 2\lambda_{34}\xi_u\xi_d\right)} \tag{23}$$

> Scalar perturbation amplitude $P_\zeta \sim 10^{-10}$ for $\lambda_{\text{eff}} \sim \mathcal{O}(1) \to \xi_{\text{eff}} \sim 10^5$

Mixed-Higgs Inflation in 2hdSMASH

> Conditions for global minimum:

$$\lambda_1\xi_2 - \lambda_{34}\xi_1 > 0\ ,\ \lambda_2\xi_1 - \lambda_{34}\xi_2 > 0\ ,\ \lambda_1\lambda_2 - \lambda_{34}^2 > 0 \qquad (24)$$



Higgs-Hidden-Scalar Inflation in 2hdSMASH

- So far: ρ-Inflation, h_u-Inflation (similarly h_d-Inflation)
- Mixed-Higgs Inflation: $h_u h_d$-Inflation
- Higgs-Hidden-Scalar Inflation: ρh_u-Inflation, ρh_d-Inflation and $\rho h_u h_d$-Inflation
- ρh_u-Inflation:

$$V_{4,\rho h_u} = \lim_{\substack{\beta \to 0 \\ \gamma \to \gamma_{\text{2HDM}}}} V_4 \simeq \frac{\lambda_1 \lambda_\sigma - \lambda_{1\sigma}^2}{8\left(\xi_\sigma(\lambda_1 \xi_\sigma - 2\lambda_{1\sigma}\xi_1) + \lambda_\sigma \xi_1^2\right)} \tag{25}$$

Higgs-Hidden-Scalar Inflation in 2hdSMASH

> Boundedness from below and perturbativ unitarity conditions:

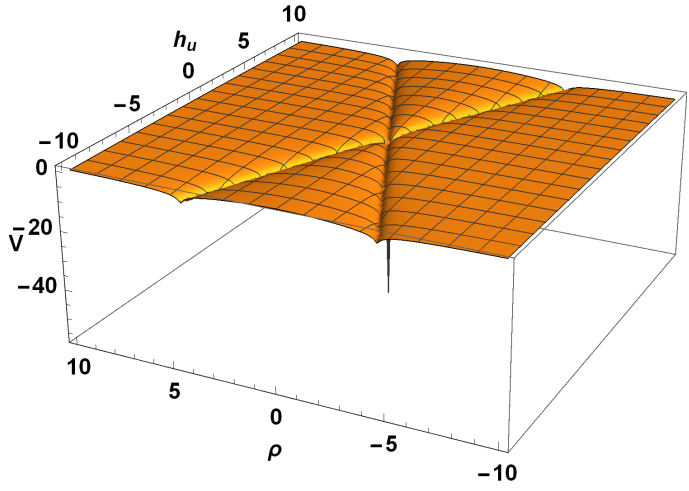
$$\lambda_1, \lambda_\sigma > 0 \ , \ \lambda_{34}^2 < \lambda_2 \left(\lambda_1 - \frac{\lambda_{1\sigma}^2}{\lambda_\sigma} \right) \ , \ |\lambda_{1\sigma}| < 8\pi \tag{26}$$

> Global minimum conditions:

$$\lambda_{1\sigma}\xi_1 - \lambda_1\xi_\sigma > 0 \ , \ \lambda_{1\sigma}\xi_\sigma - \lambda_\sigma\xi_1 > 0 \ , \ \lambda_1\lambda_\sigma - \lambda_{1\sigma}^2 > 0 \tag{27}$$

> $P_\zeta \sim 10^{-10}$ for $\lambda_{\text{eff}} \sim 10^{-10}$ and $\xi_{\text{eff}} \sim 1$

Higgs-Hidden-Scalar Inflation in 2hdSMASH



Conclusions & Outlook

- 2hdSMASH contains 7 inflationary scenarios: h_u, h_d, $h_u h_d$, ρ, ρh_u, ρh_d and $\rho h_u h_d$
- Inflationary scenarios of the 2HDM (h_u, h_d, $h_u h_d$) not viable without m_{12}-term $\longrightarrow$ 4 viable inflationary scenarios in 2hdSMASH (ρ, ρh_u, ρh_d and $\rho h_u h_d$)
- Investigation of the inflationary epoch and the subsequent Reheating epoch can tell us more about the PQ-scale (work in progress)

Thank you!

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