Inflation and Higgs Phenomenology in a Model Unifying the DFSZ Axion with the Majoron

- **Motivation**
- **Model under study**
- **Phenomenology**
- **Conclusions**

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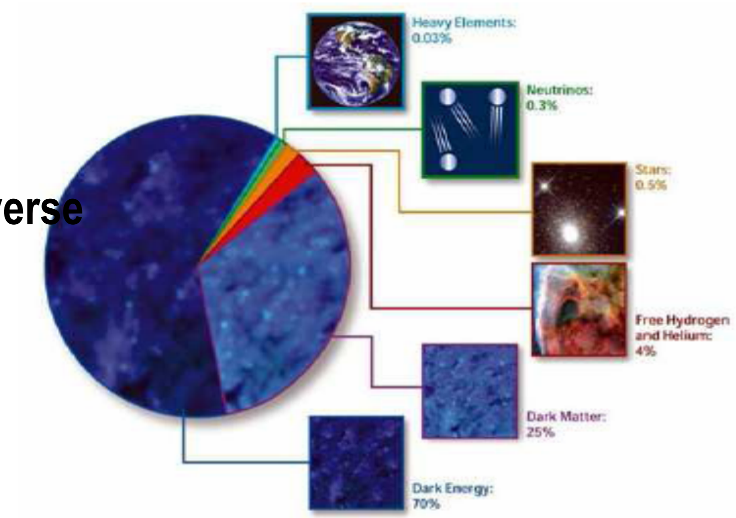
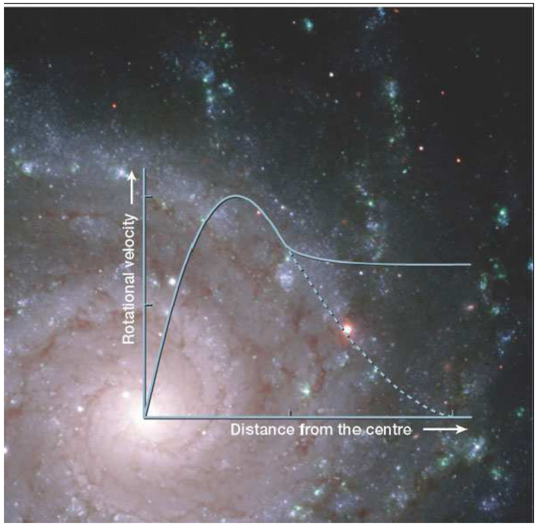
talk based on: JCAP07 (2924) 007, 2309.10857

Motivation

- ***Open Questions***
  - *Dark Matter (DM)*
    - **Only 4.6% 'known' of Universe**
    - **about 24% Dark Matter**
    - **about 71.4% Dark Energy**



  - *Hierarchy problem*
  - *Grand Unification*
  - *No Strong CP-violation*
  - *Neutrino Masses*
  - *Baryon-Antibaryon Asymmetry*
  - *Inflationary period before thermal radiation*



➡ **BSM physics required !**

Extended two Higgs doublet models

- **Status LHC:**
  - one Higgs particle discoveres in 2012
    - strongly consistent with Standard Model (SM) predictions
  - Few excesses around
    - not yet confirmed signals for new physics
  - let's concentrate on SM with extended scalar and singlet sectors
- **SM with gauge singlet scalars: natural DM candidates**
  - strong constraints from direct detection searches
  - suitable for extended Higgs sectors with heavy Higgs portal to dark sector
  - extended SMASH (SM+3 singlet ν_R + axion+exotic quark) models
- Aside: extra singlets allow to accommodate matter-antimatter asymmetry, inflation and neutrino masses

Model: 2hdSMASH

Volkas, Davies, Joshi '88
Clarke, Volkas '16
Espriu, Mescia, Renau '15

- ***2hdSMASH= $U(1)_{PQ}$-sym. 2 Higgs Doublets***
  + 1 complex singlet scalar S
  + 3 singlet Majorana ν_R
- **This model solves:**
  - ***Strong CP via PQ mechanism***
  - ***Dark matter via axion***
  - ***Neutrino masses via seesaw***
  - ***Baryon Asymmetry via leptogenesis***
  - ***Inflationary phase via Higgs portals***

➡ ***here: combine inflationary constraints with Higgs phenomenology***

The scalar potential

$$
\begin{aligned}
V(\Phi_1, \Phi_2, S) = {} & M_{11}^2\, \Phi_1^\dagger \Phi_1 + M_{22}^2\, \Phi_2^\dagger \Phi_2 + M_{SS}^2\, S^* S \\
& + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2\right)^2 + \frac{\lambda_S}{2} (S^* S)^2 \\
& + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right) \left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right) \left(\Phi_2^\dagger \Phi_1\right) \\
& + \underline{\lambda_{1S}} \left(\Phi_1^\dagger \Phi_1\right) (S^* S) + \underline{\lambda_{2S}} \left(\Phi_2^\dagger \Phi_2\right) (S^* S) \\
& \underline{- \lambda_{12S}} \left(\Phi_2^\dagger \Phi_1 S^2 + h.c.\right) ,
\end{aligned}
$$

$\Phi_i = \begin{pmatrix} \phi_i^\pm \\ \frac{1}{\sqrt{2}}(v_i + H_i + iA_i) \end{pmatrix}$ with $\sqrt{v_1^2 + v_2^2} \equiv v \simeq 246\,\mathrm{GeV}$ and $S = \frac{1}{\sqrt{2}}(v_S + H_S + iA_S)$ with $v_S \gg v$

➡Portal couplings important for neutrino masses and inflation

$$
-\mathcal{L}_Y = Y_u \overline{q_L} \tilde{\Phi}_2 u_R + Y_d \overline{q_L} \Phi_1 d_R + Y_e \overline{l_L} \Phi_1 e_R + Y_\nu \overline{l_L} \tilde{\Phi}_1 N_R + \frac{1}{2} y_N \overline{(N_R)^c} S N_R + \mathrm{h.c.}
$$

Scalar particle sector

- ***10 d.o.f leading to 7 scalar particles after EWSB***
  - ***charged Higgs*** $$m_{H^\pm}^2 = \frac{1}{2}\left(\frac{\left(t_\beta^2+1\right)\lambda_{12S}}{t_\beta} - \frac{\lambda_4 v^2}{v_S^2}\right) v_S^2$$
  - ***CP-odd scalars: axion = Nambu-Goldstone boson, mass via mixing with π^0*** $$m_a \simeq \frac{\sqrt{z}}{1+z}\frac{m_\pi f_\pi}{f_a} \simeq 0.57\,\mathrm{meV}\left(\frac{10^{10}\,\mathrm{GeV}}{f_a}\right)$$
  - ***with axion decay constant:*** $$f_a = \frac{\sqrt{v_S^2 + 4\frac{v_1^2 v_2^2}{v^2}}}{6}$$
  - ***one more CP-odd A:*** $$m_A^2 = \frac{2\lambda_{12S}}{1+t_\beta^2}\left(\frac{\left(1+t_\beta^2\right)^2}{4t_\beta} + \frac{v^2}{v_S^2}t_\beta\right) v_S^2$$ ***with $\lambda_{12S} \geq 0$ ('no tachyions')***
  - ***and 3 CP-even Higgs h, H and S***

Constraints I

- ## *Theoretical Constraints:*
  - *Higgs potential boundedness from below (BFB): guarantees that potential >0 in all field directions for large field values*
    - *constraints for all λ's, in particular:*

$$\lambda_{1S} > 0, \qquad \lambda_{2S} > 0, \qquad \lambda_{1S}\lambda_{2S} - \lambda_{12S}^2 > 0$$

  - *perturbative unitarity: bounds for all λ's, in particular:*

$$0.28 \lesssim \tan\beta \lesssim 140$$

  - *astrophysical/cosmological constraints: $v/v_S \ll 1$*
    - *very light axion $m_a \sim 1/v_S$, $m_h=125 \sim v$ and $m_{H,A,H^\pm,S} \sim v_S$*

- ## *Experimental Constraints:*
  - *all bounds from LEP, LHC… (HiggsTools),astrophysical (PLANCK/BICEP)*

Inflation in 2hdSMASH

- **2hdSMASH embeds chaotic inflation:**
  - *offers plateau-like scalar potential at high field values*
  - *hosts slow-roll regime for the fields*
  - *automatic feature since Φ_1, Φ_2, S ~ non-minimally coupled to Ricci R:*

$$S_{\rm 2hdSMASH} \supset -\int d^4x\sqrt{-g}\left(\frac{M^2}{2}+\xi_1\left|\Phi_1\right|^2+\xi_2\left|\Phi_2\right|^2+\xi_S\left|S\right|^2\right)R,$$

  - *Jordan to Einstein frame transformation: quartic potential ~ asymp. flat&convex*

$$\tilde{V}_{\rm quartic}(h_1,h_2,s,\tilde{\theta}_1) = \frac{\lambda_1 h_1^4+\lambda_2 h_2^4+\lambda_S s^4+2\left(\lambda_{34}h_1^2h_2^2+\lambda_{1S}h_1^2s^2+\lambda_{2S}h_2^2s^2-2\lambda_{12S}h_1h_2s^2\cos(\tilde{\theta})\right)}{8\left(1+\frac{\xi_1h_1^2+\xi_2h_2^2+\xi_S s^2}{M_{\rm P}^2}\right)^2}$$

  - *Potential and directions can be parametrized by two angles (ϑ,γ)*

$$J\left(\vartheta,\gamma\right)=\left(\frac{\partial\tilde{V}_{\rm quartic}(\vartheta,\gamma)}{\partial\vartheta}\;\;\frac{\partial\tilde{V}_{\rm quartic}(\vartheta,\gamma)}{\partial\gamma}\right)^2 \;\longrightarrow\; \gamma_{0,i}=\begin{cases}\gamma_{\rm THI}=\frac{\pi}{2}\\ \gamma_{\rm PQI}=0\\ \gamma_{\rm PQTHI}=\gamma_{\rm PQTHI}(\vartheta)\end{cases}$$

Inflationary Directions

inflation along	Potential minimized at	Inflationary conditions	Einstein frame slow roll potential
$s\,h_1$	$\gamma_0 = \arctan\left(\sqrt{-\frac{\lambda_{1S}}{\lambda_1}}\right)$ $\vartheta_0 = 0$	$\kappa_{s1} \geq 0\,,\quad \kappa_{s2} \leq 0$ $\kappa_{1s} \leq 0\,,\quad \kappa_{2s} \geq 0$	$\frac{\lambda_{sh_1}}{8} s^4 \left(1 + \xi_S \frac{s^2}{M_P^2}\right)^{-2}$
$s\,h_2$	$\gamma_0 = \arctan\left(\sqrt{-\frac{\lambda_{2S}}{\lambda_2}}\right)$ $\vartheta_0 = \frac{\pi}{2}$	$\kappa_{s1} \leq 0\,,\quad \kappa_{s2} \geq 0$ $\kappa_{1s} \geq 0\,,\quad \kappa_{2s} \leq 0$	$\frac{\lambda_{sh_2}}{8} s^4 \left(1 + \xi_S \frac{s^2}{M_P^2}\right)^{-2}$
$s\,h_{12}$	$\gamma_0 = \arctan\left(\sqrt{-\frac{\kappa_{s2}+\kappa_{s2}}{\lambda_1\lambda_2-\lambda_{34}^2}}\right)$ $\vartheta_0 = \arctan\left(\sqrt{\frac{\kappa_{s1}}{\kappa_{s2}}}\right)$	$\kappa_{s1} \leq 0\,,\quad \kappa_{s2} \leq 0$ $\kappa_{1s} \leq 0\,,\quad \kappa_{2s} \leq 0$	$\frac{\lambda_{sh_{12}}}{8} s^4 \left(1 + \xi_2 \frac{s^2}{M_P^2}\right)^{-2}$
s	$\gamma_0 = 0$ $\vartheta_0 = \{0, \frac{\pi}{2}\}$	$\kappa_{1s} \geq 0\,,\quad \kappa_{2s} \geq 0$ $\vee\ \lambda_{1S,2S} \ll \lambda_S$	$\frac{\lambda_S}{8} s^4 \left(1 + \xi_S \frac{s^2}{M_P^2}\right)^{-2}$

Table: Conditions and characteristics for PQI and PQTHI, i.e. s- and $sh_{1,2,12}$-inflation, with $\xi_S \gg \xi_{1,2}$.

Sign of portal couplings essential in deciding inflationary direction.

M.Matlis, DESY-THESIS-2022-022

Inflationionary dynamics (Constraints II)

- ***Further constraints on portal couplings/parameters:***
  - ***use inflationary parameters as spectral tilt n_s and tensor-to-scalar ratio r***

$$4.5 \times 10^{-13} \lesssim \tilde{\lambda}_S \lesssim 8 \times 10^{-10}$$

$$8 \times 10^{-3} \lesssim \xi_S \lesssim 1$$

- ***Stability constraints:***

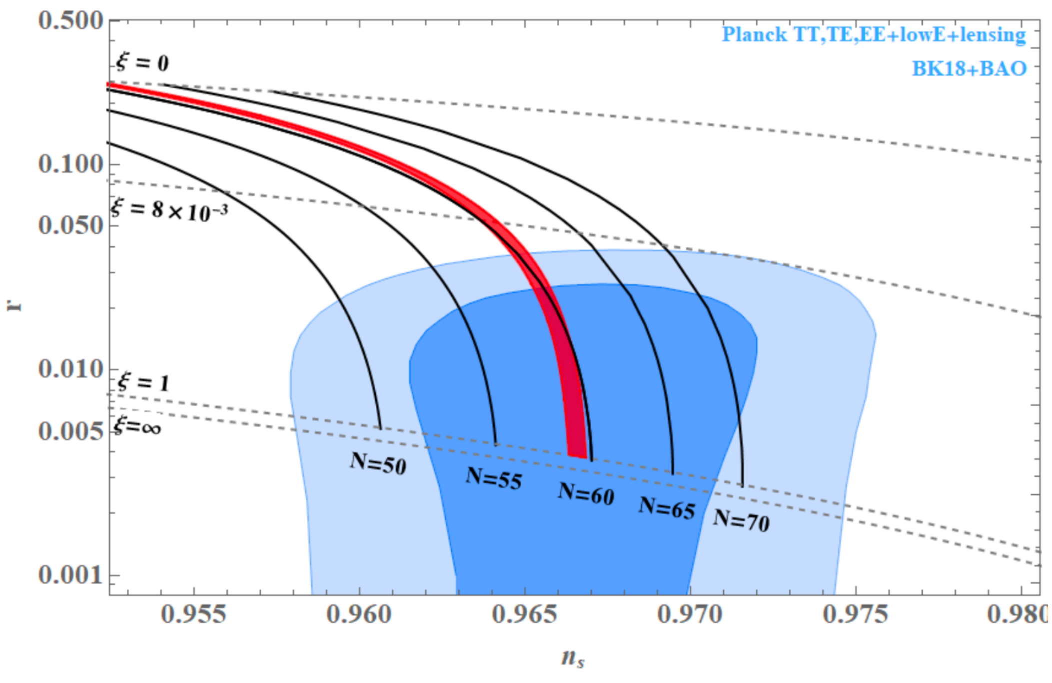
From stability of λ_S

$$\left.\begin{array}{l} |\lambda_{1S}(m_s)| \\ |\lambda_{2S}(m_s)| \\ |\lambda_{12S}(m_s)| \\ \sqrt{\mathrm{Tr}\left(Y_N^\dagger Y_N Y_N^\dagger Y_N\right)_{|m_s}} \end{array}\right\} \ll \sqrt{\lambda_S(m_s)} \approx 10^{-5}$$

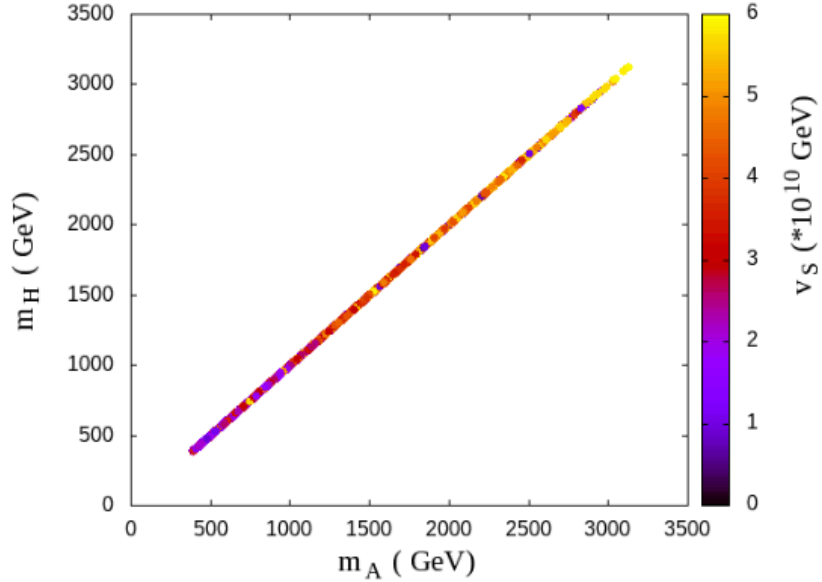
implying $\lambda_S(M_P) \approx \lambda_S(m_s) \approx 10^{-10}$.

Inflation vs TeV Phenomenology

- **One-loop RGEs required:**
  - *run 2hdSMASH parameters from low-to-high-scale*
  - *ensure successful inflation at Planck scale, i.e.* $\lambda_S(M_{\rm P}) \lesssim 10^{-10}$
  - *stable evolution from matching scale to* M_P
  - *portal couplings get tight constraints !*



Particle Spectra



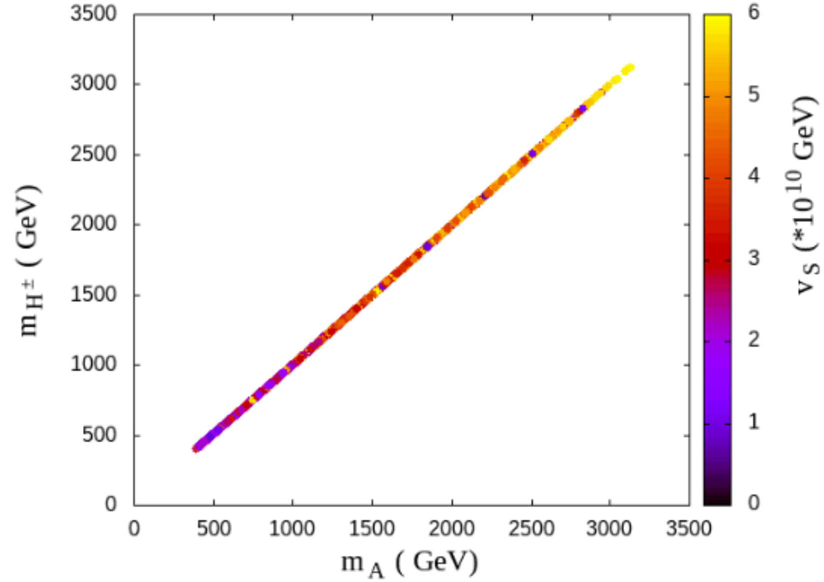


Figure: Distributions for m_H vs. m_A plane for $\tan\beta = 5$.

$m_H \sim m_A \sim m_H^{\pm}$, naturally compressed spectrum due to $v_s \gg v$.

$\lambda_{12S} \sim 10^{-16} - 10^{-15} \implies$ phenomenological spectra with m_H, m_A and $m_H^{\pm}$ within the reach of HL-LHC!

Particle Spectra

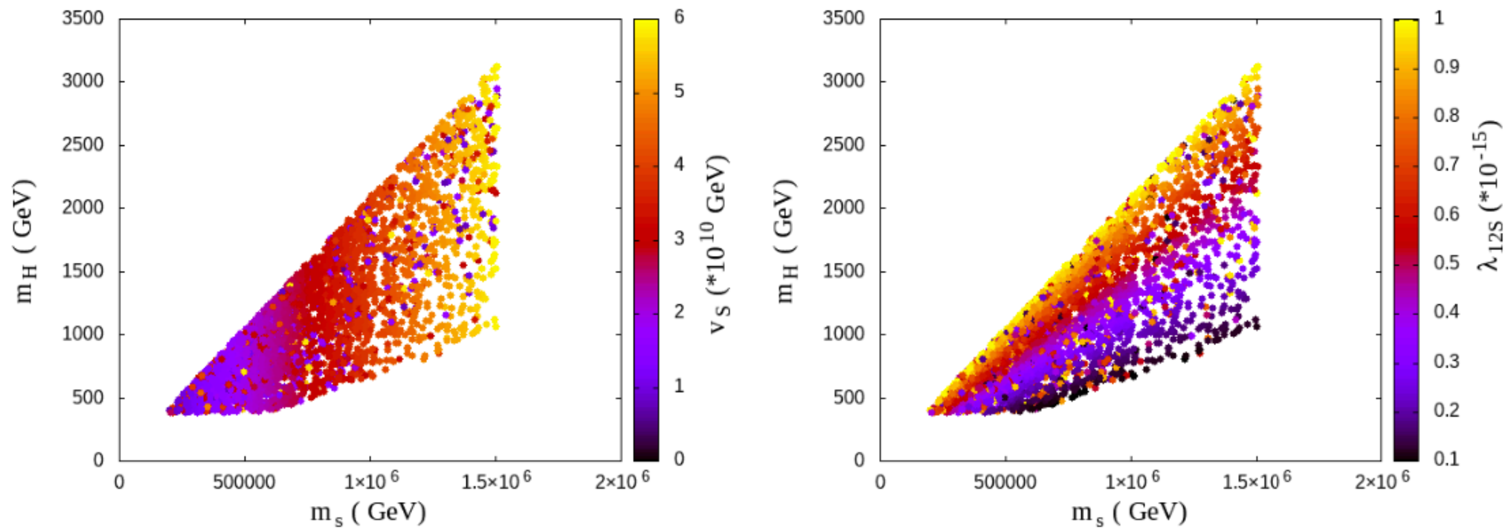


Figure: Variation of m_H vs. m_s plane for $\tan\beta = 5$. The colour palette denotes v_S and λ_{12S} respectively.

m_H, m_s increases with increase in v_S and λ_{12S}.

also pointed out in Espriu et.al,Phys. Rev. D 92, 095013 (2015) for DFSZ models without inflationary dynamics

Importance of tan β

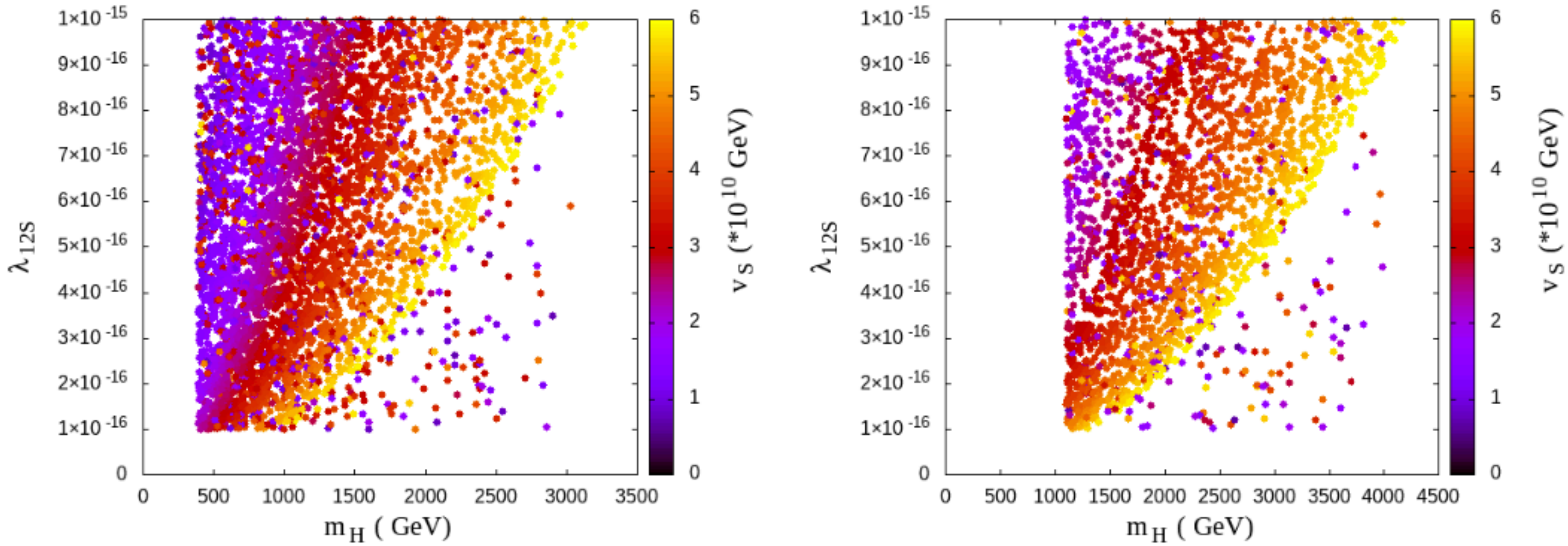


Figure: Variation of λ_{12S} vs. m_H for $\tan\beta = 5, 10$.

The low energy spectra fully determined by λ_{12S}, v_S and $\tan\beta$.

Benchmarks

All theo.&exp. constraints fulfilled!

Parameters	**BP1**	**BP2**	**BP3**	**BP4**	**BP5**
λ_1	0.07	0.07	0.07	0.07	0.07
λ_2	0.287	0.263	0.257	0.258	0.257
λ_3	0.54	0.60	0.24	0.54	0.24
λ_4	-0.14	-0.4	0.27	-0.14	-0.28
λ_S	4.44×10^{-10}	6.5×10^{-10}	1.0×10^{-10}	1.0×10^{-10}	1.0×10^{-10}
λ_{1S}	5.57×10^{-6}	-6.59×10^{-6}	4.8×10^{-14}	4.8×10^{-14}	3.6×10^{-13}
λ_{2S}	-4.27×10^{-6}	1.0×10^{-15}	1.0×10^{-15}	1.0×10^{-15}	1.0×10^{-15}
λ_{12S}	2.5×10^{-16}	2.5×10^{-16}	2.5×10^{-16}	2.5×10^{-16}	2.5×10^{-16}
$\tan\beta$	5.5	5.5	26	26	18
$Y_{N,1}$	9×10^{-4}	9×10^{-4}	4×10^{-5}	4×10^{-5}	10^{-4}
$Y_{\nu,3}$	5.175×10^{-3}	5.175×10^{-3}	1.09×10^{-3}	1.09×10^{-3}	1.2×10^{-3}
v_S	3.0×10^{10}	3.0×10^{10}	3.0×10^{10}	3.0×10^{10}	3.0×10^{10}
m_h (GeV)	125.2	125.3	125.0	124.9	125.4
m_H (GeV)	798.7	799.4	1711.5	1711.5	1425.2
m_s (GeV)	6.3×10^5	6.7×10^5	3.0×10^5	3.0×10^5	3.0×10^5
m_A (GeV)	799.5	799.5	1711.5	1711.5	1425.2
$m_{H^\pm}$ (GeV)	802.1	807.0	1709.1	1712.8	1422.2

Conclusion & Outlook

- ***Inflation in singlet direction: $\lambda_S \sim 10^{-10}$***
  - *stringent constraints (also from BFB) on portal couplings!*
- ***Favoured range for λ_{12S}, v_S, $\tan\beta$ for heavy Higgs'***
  - *axionic DM and relic thermal abundance: $v_S \sim O(10^9\text{-}10^{10})$ GeV*
  - *large hierarchie between v, v_S: compressed heavy Higgs spectra*
  - *accessible at HL-LHC, or TeV ILC/CLIC/muC…..*
- ***Indication for preferred direction of inflation***
  - *impact of accomodating phenomenological constraints*
- ***Still to do:***
  - *Preheating/reheating discussion: will effect #e-folds, PG-restoration, BAU etc.*
  - *extended collider phenomenology*