2HDM UV completions.

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2HDM.

Assuming SU(2)$_L$ complex doublets of the form:

$$\Phi_n = \begin{pmatrix} H_n^+ \\ (H_n^0 + iA_n^0)/\sqrt{2} \end{pmatrix},$$

$$\begin{aligned}\mathcal{V} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] \\ & + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \left\{ \tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)\right] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\} .\end{aligned}$$

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2HDM.

After EWSB takes place, $\tan\beta = v_2/v_1 \quad v^2 = v_1^2 + v_2^2 = (246)^2\,\mathrm{GeV}$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}$$

CP-odd Higgs: $A = -\eta_1 \sin\beta + \eta_2 \cos\beta \qquad m_A^2 = \dfrac{2m_{12}^2}{\sin 2\beta} - \lambda_5 v^2$

Charged Higgs: $H^+ = -\phi_1^+ \sin\beta + \phi_2^+ \cos\beta \qquad m_{H^\pm}^2 = m_A^2 + \dfrac{1}{2}v^2(\lambda_4 - \lambda_5)$

CP-even Higgses: $$\mathcal{M}^2 = \begin{pmatrix} \lambda_1 v^2 c_\beta^2 + \left(M_A^2 + \lambda_5 v^2\right) s_\beta^2 & \left[\lambda_{345} v^2 - \left(M_A^2 + \lambda_5 v^2\right)\right] s_\beta c_\beta \\ \left[\lambda_{345} v^2 - \left(M_A^2 + \lambda_5 v^2\right)\right] s_\beta c_\beta & \lambda_2 v^2 s_\beta^2 + \left(M_A^2 + \lambda_5 v^2\right) c_\beta^2 \end{pmatrix}$$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \sin\alpha & \cos\alpha \\ \cos\alpha & -\sin\alpha \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$$

2HDM.

One can make use of the parameters, $m_{H^\pm}$, m_A, m_H, m_h, α, β, m_{12}^2, instead of the ones that appear in the Lagrangian.

The fermionic Lagrangian can be written:

$$-\mathcal{L}_{\text{Yuk}} = \sum_{i=1}^{2} \left[\overline{Q}_L \widetilde{\Phi}_i \eta_i^U U_R + \overline{Q}_L \Phi_i \eta_i^D D_R + \overline{L}_L \Phi_i \eta_i^L E_R + \text{h.c.} \right]$$

	u-type	d-type	leptons	Q	u_R	d_R	L	l_R
type I	Φ_2	Φ_2	Φ_2	$+$	$-$	$-$	$+$	$-$
type II	Φ_2	Φ_1	Φ_1	$+$	$-$	$+$	$+$	$-$
lepton-specific	Φ_2	Φ_2	Φ_1	$+$	$-$	$+$	$+$	$-$
flipped	Φ_2	Φ_1	Φ_2	$+$	$-$	$-$	$+$	$+$

2HDM.

The 2HDM is already a theory that could be considered as UV completed.

However, one can imagine more complicated theories which effective theories at low energy are realisations of the 2HDM.

So the study of 2HDM can be a hint to guess which UV theories are possible or not, since all the constraints acting in the effective field theory will affect the theory in which is embedded.

Examples of this are SUSY, axion models, composite Higgs models, etc.

SUSY.

The superpotential of the MSSM

$$W_{\rm MSSM} = \overline{u}\mathbf{y_u}QH_u - \overline{d}\mathbf{y_d}QH_d - \overline{e}\mathbf{y_e}LH_d + \mu H_u H_d \, .$$

The Lagrangian after supersymmetry is broken reads

$$V_H = \frac{1}{8}(g_2^2 + g_Y^2)(|H_D|^2 - |H_U|^2)^2 + \frac{1}{2}g_2^2|H_D^\dagger H_U|^2 + |\mu|^2(|H_D|^2 + |H_U|^2)$$
$$+ m_{11}^2|H_D|^2 + m_{22}^2|H_U|^2 + m_{12}^2(H_D \cdot H_U + \text{h.c.}) \, ,$$

$$H_D \cdot H_U = \epsilon_{ab} H_D^a H_U^b \qquad \Phi_1 = -i\sigma_2 H_D^* \, , \qquad \Phi_2 = H_U$$

$$|H_D^\dagger H_U|^2 \to |\Phi_1|^2|\Phi_2|^2 - (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \, , \qquad H_D \cdot H_U \to -\Phi_1^\dagger \Phi_2 \, ,$$

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$$\begin{aligned} \lambda_1 = \lambda_2 = \frac{1}{4}(g_2^2 + g_Y^2)\,, \quad & \lambda_4 = -\frac{1}{2}g_2^2\,, \\ \lambda_3 = \frac{1}{4}(g_2^2 - g_Y^2)\,, \quad & \lambda_5 = 0\,, \end{aligned}$$

Now the couplings are no longer free and depend on the parameters of the UV theory. This reduces the freedom since the parameters should match at the energy in which the effective theory is no longer valid.

SUSY.

For that reason is really important to know how the different parameters of the theory run with respect the energy. One should be careful considering the RGEs and also the matching conditions at the matching scale Λ.

In the running one should also consider the corrections induced by superparticles that are heavy but could lead to corrections to the parameters. Some examples about this are: hep-ph/9307201, 0901.2065, 1508.00576

Let us focus on the study done in 1807.07581, where they perform the running of the parameter at 2-loop and consider matching conditions also at 2-loop.

SUSY.

In order to be general

$$
\begin{aligned}
W &= \lambda \hat{S}\hat{H}_d\hat{H}_u + \mu \hat{H}_d\hat{H}_u + W_Y \\
-\mathcal{L}_{\rm SB} - \mathcal{L}_{{\rm SB},\tilde{f}} &= m^2_{H_d}|H_d|^2 + m^2_{H_u}|H_u|^2 + m^2_S|S|^2 \\
&+ B_S S^2 + T_\kappa S^3 + LS + \text{c.c.}
\end{aligned}
$$

So in that case the parameters are defined as:

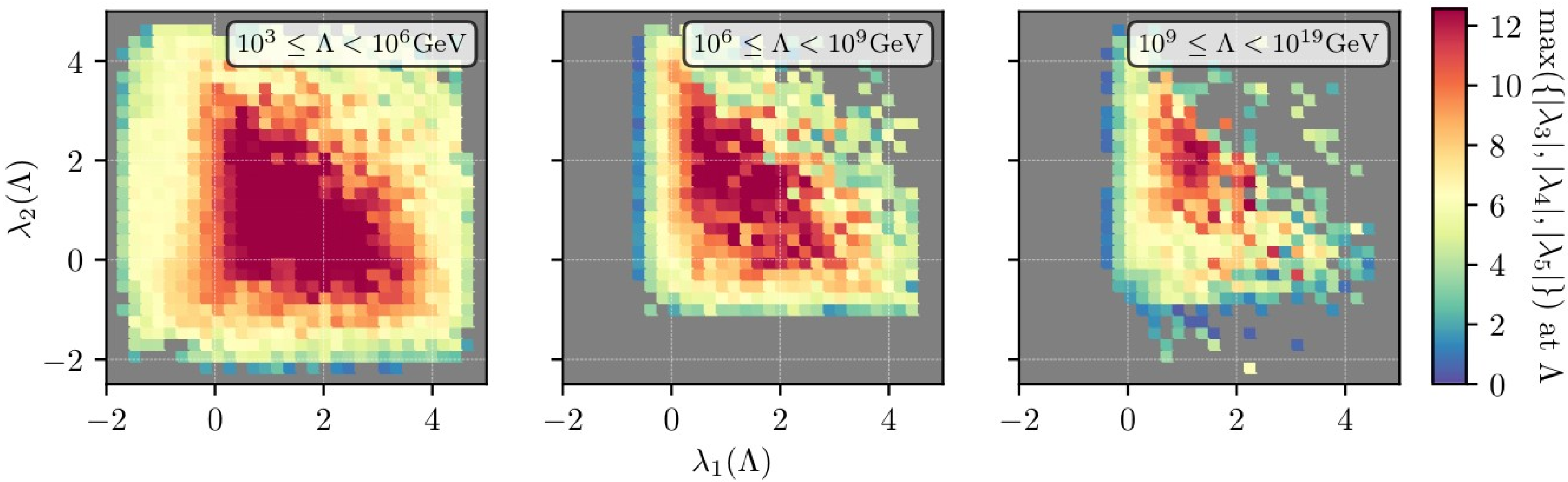
$$
\lambda_1 = \lambda_2 = \frac{1}{8}\left(g_1^2 + g_2^2 + \frac{4\sqrt{2}\lambda^2\mu^2}{M^2}\right), \qquad \lambda_4 = -\frac{1}{2}g_2^2 + \lambda^2,
$$

$$
\lambda_3 = \frac{1}{4}\left(-g_1^2 + g_2^2 + \frac{12\sqrt{2}\lambda^2\mu^2}{M^2}\right), \qquad \lambda_5 = 0,
$$

$$
\lambda_i(\Lambda) \in [-4\pi, 4\pi],
$$

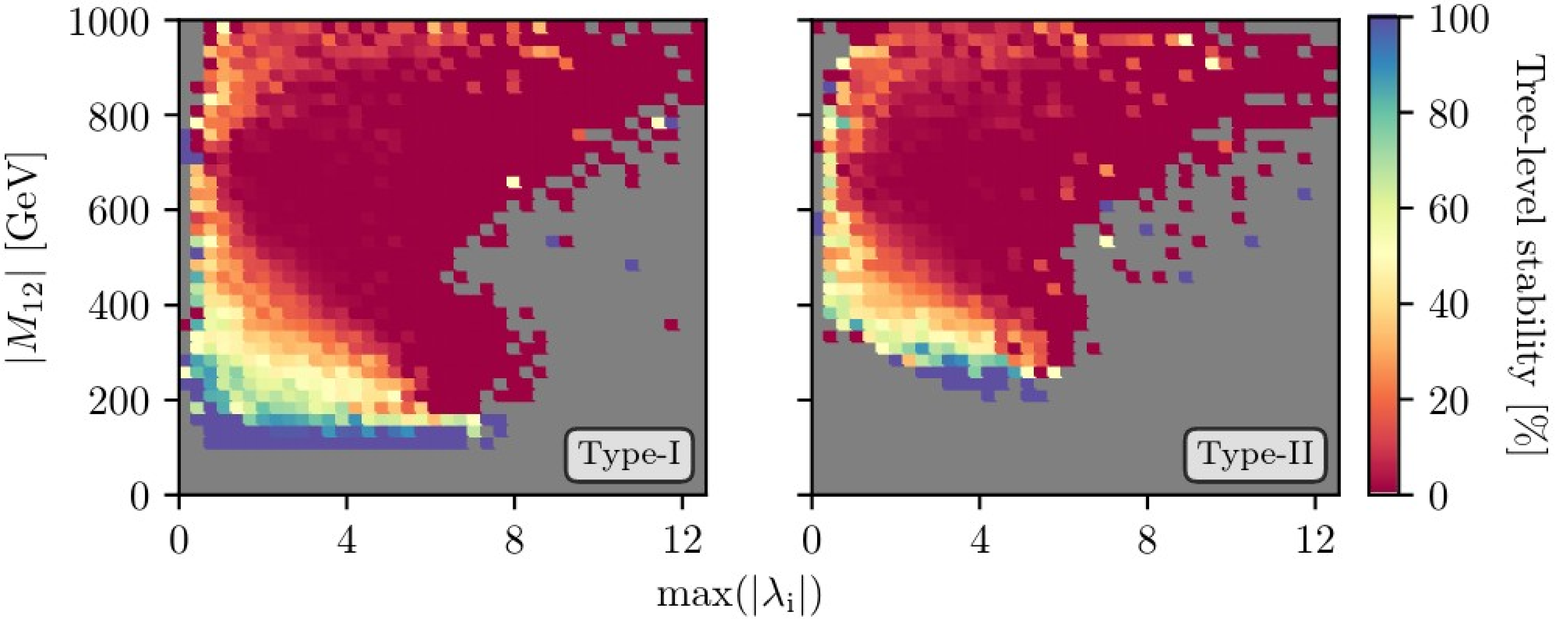
SUSY.

Maximum for the values of the couplings as a function of the matching scale



SUSY.

Stability bounds when considering tree-level vs. one-loop vacuum stability constraints.



Axions.

In order to solve the strong CP-problem, one can invoke the Peccei-Quinn mechanism. There exist a new abelian global symmetry $U(1)_{PQ}$ that is spontaneously broken at f_a scale, originating a pseudo-Goldstone boson, the axion.

$$\mathcal{L} = \frac{a}{f_a}\frac{\alpha}{8\pi}G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

$$\mathcal{L}_{\mathrm{a}}^{\mathrm{eff}} = \frac{1}{2}\partial_\mu \hat{a}\partial^\mu \hat{a} - \frac{\alpha_{em}}{8\pi}\frac{E}{N}\frac{\hat{a}}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{\alpha_s}{8\pi}\frac{\hat{a}}{f_a}G_{a\mu\nu}\tilde{G}_a^{\mu\nu} + \partial_\mu \hat{a}\sum_i \chi_i\left(\overline{\psi}_i\gamma^\mu\psi_i\right)$$

The SM does not have an abelian global U(1) symmetry that could be only broken by the QCD anomaly. The SM needs to be extended.

PQWW.

(Peccei-Quinn-Weinberg-Wilczek)

One of the first ideas was to extend the Higgs sector adding an extra Higgs doublet.

$$H_u = \left(\mathbf{1}, \mathbf{2}, \frac{1}{2}\right) \qquad\qquad H_d = \left(\mathbf{1}, \mathbf{2}, \frac{1}{2}\right)$$

Leptons can now couple to both of the doublets (type II and flipped 2HDM)

The Yukawa sector of type II reads:

$$\mathcal{L}_{\text{Yukawa}} - \overline{Q}_L Y_u \widetilde{H}_u U_R - \overline{Q}_L Y_d H_d D_R - \overline{\ell}_L Y_e H_d E_R + \text{h.c.}$$

$$\begin{aligned} U(1)_{\text{PQ}}: \quad & Q_L \to e^{i\chi_q \alpha} Q_L, & U_R \to e^{i\chi_u \alpha} U_R, \quad & D_R \to e^{i\chi_d \alpha} D_R, \\ & \ell_L \to e^{i\chi_\ell \alpha} \ell_L, & E_R \to e^{i(\chi_\ell - \chi_q + \chi_d)\alpha} E_R\,, & \\ & H_u \to e^{i(\chi_u - \chi_q)\alpha} H_u\,, & H_d \to e^{i(\chi_q - \chi_d)\alpha} H_d\,, & \end{aligned}$$

$$\chi_q = \chi_\ell = 0 \qquad\qquad \chi_u, \chi_d$$

PQWW.

(Peccei-Quinn-Weinberg-Wilczek)

After EWSB takes place we have a pseudo-Goldstone boson (PQ is also broken)

$$f_{\rm PQ} a = -\chi_u v_u\, a_u + \chi_d v_d\, a_d \quad , \qquad f_{\rm PQ} = \sqrt{\chi_u^2 v_u^2 + \chi_d^2 v_d^2}\ .$$

Imposing invariance under $U(1)_Y$ $\rightarrow$ $\frac{\chi_u}{\chi_d} = \frac{v_d^2}{v_u^2}$

$$\mathcal{L}_{\rm PQWW} \supset N_f \left(x + \frac{1}{x}\right) \frac{\alpha_s}{8\pi} \frac{a}{f_{\rm PQ}} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$x = v_d/v_u$$

$$\chi_u = x\,, \qquad \chi_d = \frac{1}{x}$$

This makes f_{PQ} to be of the order of the EW scale and m_a~keV. The visible axion is easily ruled out by several experimental observations, such as:

$$K^+ \to \pi^+ a \qquad\qquad K^+ \to \pi^+ \text{inv}$$

DFSZ.

(Dine-Fischler-Srednicki-Zhitnitsky)

A complex scalar is added to the PQWW model

$$V(H_u, H_d, \sigma) = \frac{\lambda_\sigma}{2}|\sigma|^4 + \delta_1 (H_u^\dagger H_u)|\sigma|^2 + \delta_2 (H_d^\dagger H_d)|\sigma|^2 + \delta_3 (H_u^\dagger H_d)\sigma^2 + \delta_3 (H_d^\dagger H_u)\sigma^{*2}$$

$$\mathrm{U}(1)_{\mathrm{PQ}}: \quad \sigma \to \mathrm{e}^{\mathrm{i}\beta\chi_\sigma}\sigma\,, \qquad \chi_\sigma = \frac{1}{2}(\chi_u + \chi_d)$$

If one assumes that the corresponding vev of σ is much larger than the EW scale

$$a = \frac{1}{f_{\mathrm{PQ}}}\left(-\chi_u v_u\, a_u + \chi_d v_d\, a_d + \chi_\sigma v_\sigma\right) \xrightarrow{v_\sigma \gg v_d, v_u} a_\sigma$$

$$f_{\mathrm{PQ}} = \sqrt{\chi_u^2 v_u^2 + \chi_d^2 v_d^2 + \chi_\sigma^2 v_\sigma^2} \xrightarrow{v_\sigma \gg v_d, v_u} \chi_\sigma v_\sigma$$

$$N = 3\,(\chi_u + \chi_d) = 6\,, \qquad E = 16 \quad \Longrightarrow \quad \frac{E}{N} = \frac{8}{3}\,.$$

SMASH.

- Higgs portal inflation
- Seesaw
- Axions
- SM

$$\mathcal{L} \supset -\left[Y_{uij} q_i \epsilon H u_j + Y_{dij} q_i H^\dagger d_j + G_{ij} L_i H^\dagger E_j + F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j \right.$$
$$\left. + \, y \, \tilde{Q} \sigma Q + y_{Q_d i} \sigma Q d_i + h.c. \right],$$

It could be promoted to a 2HDM (2dhSMASH) with the possibility that the leptons could couple to H_u or H_d

In Grand Unified theories the leptons usually couple to H_d

In SMASH one has the relation $f_A = v_\sigma / 6$

GUTs.

SU(5)

In SU(5) fermions are in the 10_F and 5_F, the scalar 24_H breaks SU(5) and the ones in 5_H originate EWSB. This theory is pretty much constrained by proton decay. This could be avoided adding a fermionic multiplet in the 24_F.

$$\mathcal{L} \supset \bar{5}_F 10_F 5'^*_H + 10_F 10_F 5_H + \bar{5}_F 24_F 5_H + \mathrm{Tr} 24_F^2 24_H^* + 5'^*_H 24_H^2 5_H + 5'^*_H 5_H \mathrm{Tr}(24_H^2) + \mathrm{h.c.}$$

The axion decay constant is related with the unification scale $f_A = v_U/11$,

$$m_A \in [4.8, 6.6]\ \mathrm{neV}.$$

GUTs.

SO(10)

In SO(10) fermions are in the 16_F and the scalars in 10_H and 126_H.

$$\mathcal{L}_Y = 16_F \left(Y_{10} 10_H + \tilde{Y}_{10} 10_H^* + Y_{126} \overline{126}_H \right) 16_F + \text{h.c.}$$

One can add another scalar multiplet in the 210_H that can trigger the breaking.

If all the multiplets are charged except the 210_H under PQ then $f_A = v/3$, leads to visible axion.

However, if the 210_H is also charged then the relation becomes $f_A = v_{\mathrm{U}}/3$

$$2.6 \times 10^{15}\text{GeV} < f_A < 3.0 \times 10^{17}\text{GeV}, \quad 1.9 \times 10^{-11}\text{eV} < m_A < 2.2 \times 10^{-9}\text{eV}$$

GUTs.

gutSMASH

In SO(10) SMASH (gutSMASH) a new scalar is added that is charged under PQ and now the 210_H remains uncharged.

Having this the decay constant of the axion depends only in the vev of σ

$$f_A = v_\sigma/3$$

Model	16_F	$\overline{126}_H$	10_H	210_H	σ
miniSO(10)PQ	1	-2	-2	4	$-$
gutSMASH	1	-2	-2	0	4