SMASH-ing Vacuum Metastability

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Problems of the SM already have possible solutions

Biggest problems in physics (grand unification not included):

1. Strong CP problem $\rightarrow$ axion [Peccei, Quinn 1977]
2. Neutrino masses $\rightarrow$ seesaw [Minkowski, Yanagida, Glashow, Gell-Mann,... 1977-80]
3. Baryonic asymmetry of the Universe $\rightarrow$ leptogenesis [Fukugita, Yanagida 1986]
4. Dark matter $\rightarrow$ sterile neutrinos, axions, ALPs, WIMPs, LSPs ...
5. Inflation $\rightarrow$ Higgs inflation, extended scalar sector
6. Vacuum metastability $\rightarrow$ extended scalar sector

Partial solutions:

Not yet a theory which combines all of the solutions together,
however νMSM [Asaka, Shaposnikov 2005] and some others are close enough

Combined solution:

SMASH combines all the solutions in one framework at mass scale $\sim 10^{11}$ GeV
[Ballesteros, Redondo, Ringwald, Tamarit 1608.05414, 1610.01639, Ringwald 1610.05040]

SM + Axion + Seesaw + Higgs portal inflation (SMASH)

Minimal model to accomodate the proposed solutions:

Gen I	u	d	e	ν_e		N_1	Q
Gen II	c	s	μ	ν_μ		N_2	
Gen III	t	b	τ	ν_τ	+	N_3	
Gauge bosons	g	W	Z	γ			
Scalars				H		A	ρ

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \quad \times \quad \mathrm{U}(1)_{\mathrm{PQ}_{\mathrm{SMASH}}}$$

1. Three heavy right-handed sterile Majorana neutrinos N_i
2. Colour triplets $Q \sim \mathbf{3}$ and $\widetilde{Q} \sim \overline{\mathbf{3}}$
3. Singlet scalar ρ
4. Axion A

Peccei-Quinn symmetry and Lagrangian

Introduction of the PQ_{SMASH} charges and Y_{SMASH} hyper-charges:

$U(1)_{PQ_{SMASH}}$	q_L	u_R	d_R	L_L	N	ℓ_R	Q	$\tilde{Q}$	σ	H
PQ_{SMASH}	1/2	$-1/2$	$-1/2$	1/2	$-1/2$	$-1/2$	$-1/2$	$-1/2$	1	0
Y_{SMASH}	1/3	$-4/3$	2/3	-1	0	2	1/3 or $-2/3$	$-1/3$ or 2/3	1	1

Induces $Q - d_R$ mixing and decay of Q to d_R:

$$-\mathcal{L}_{\text{Yukawa}} = Y^u_{ij} q_{Li} \varepsilon H u_{Rj} + Y^d_{ij} q_{Li} H^\dagger d_{Rj} + G_{ij} L_{Li} H^\dagger \ell_{Rj}$$

$$+ \underbrace{Y^F_{ij} L_{Li} \varepsilon H N_j + \frac{1}{2} Y^N \sigma N_i N_j}_{\text{neutrino mass and leptogenesis}}$$

$$+ \underbrace{Y^Q \tilde{Q} \sigma Q + y^Q_i \sigma Q d_{Ri}}_{\text{strong CP problem}} + \text{h.c.}$$

Scalar sector

Higgs portal coupling stabilizes Higgs potential by giving extra contribution to β_{λ_H}

[Gonderinger et al 2010]

or by tree-level threshold effect setting $\lambda_{H\sigma}^2/\lambda_\sigma \sim 10^{-2}$:

[Lebedev 2012, Elias-Miro et al 2012]

$$\mathcal{L}_{\text{scalar}} = -R\left(\frac{1}{2}M^2 + \xi_H H^\dagger H + \xi_\sigma|\sigma|^2\right) + \lambda_H\left(H^\dagger H - \frac{v^2}{2}\right)^2 + \lambda_\sigma\left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)^2 + \underbrace{2\lambda_{H\sigma}\left(H^\dagger H - \frac{v^2}{2}\right)\left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)}_{\text{scalar potential metastability}}$$

$$\sigma = \frac{1}{\sqrt{2}}(v_\sigma + \rho)e^{iA/v_\sigma}$$

Axion sector

Lepton number symmetry is spontaneously broken, when σ develops VEV, its phase A becoming the associated Nambu-Goldstone boson, which works as axion in SMASH, having a mass:

$$m_A \approx 57 \times \frac{10^{11}\ \text{GeV}}{f_A}\ \mu\text{eV}, \quad \text{with} \quad f_A = v_\sigma$$

1. Axion in SMASH will have a mass on the range $10 - 200\ \mu$eV
2. Axion chosen as dark matter candidate instead of sterile neutrino
3. Axion-dominated dark matter requires the axion decay constant to be in a specific interval,

   $$3 \times 10^{10}\ \text{GeV} \lesssim v_\sigma \lesssim 5 \times 10^{11}\ \text{GeV}$$

   to explain the total dark matter abundance
   1. larger $v_\sigma \Rightarrow$ overproduction of DM
   2. smaller $v_\sigma \Rightarrow$ partly axionic DM

Neutrino sector

1. Basic version of SMASH utilizes Type-I seesaw mechanism:
   [Minkowski, Yanagida, Glashow, Gell-Mann, Mohapatra,... 1977-80]

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & Y^F v \\ {Y^F}^T v & Y^N v_\sigma \end{pmatrix},$$

$$m_\nu = -M_D M_M^{-1} M_D^T = 0.04\ \mathrm{eV} \times \frac{10^{11}\ \mathrm{GeV}}{v_\sigma} \times \frac{-Y^F (Y^N)^{-1} {Y^F}^T}{10^{-4}}$$

2. Vanilla leptogenesis scenario requires the existence of heavy neutrinos, with $M_M \gtrsim 3 \times 10^8$ GeV $\Rightarrow$ too unstable to be a DM candidate
3. Seesaw scale, being intermediate between SM and GUT scales, slides well into SMASH framework, with RH neutrino mass given by VEV of σ
4. Such a heavy scale implicates negligible active-sterile mixing, making it invisible to neutrino oscillation experiments
5. Large v_σ and portal coupling will induce large corrections to μ_H^2

Visions from numerical solutions of RGE's

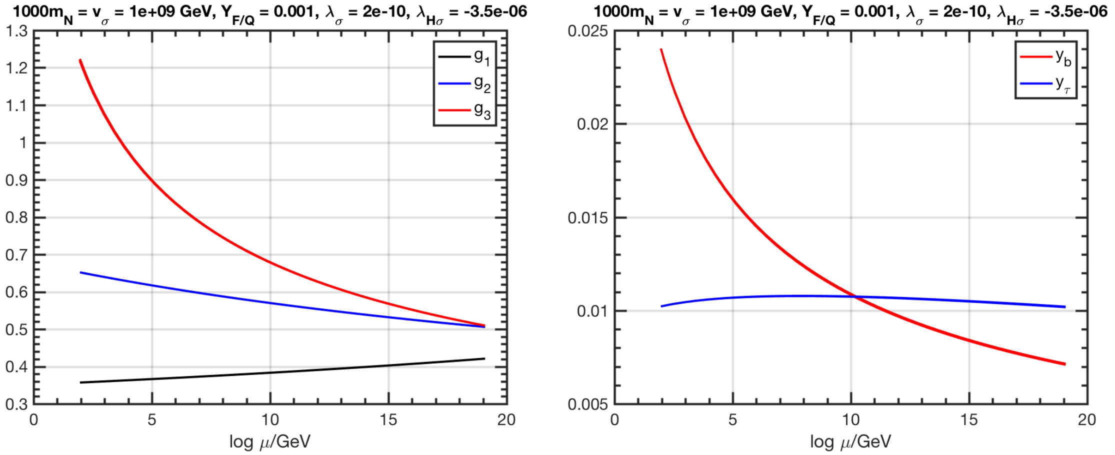
[Das, Kärkkäinen, Huitu 18XX.XXXX]

Benchmark point

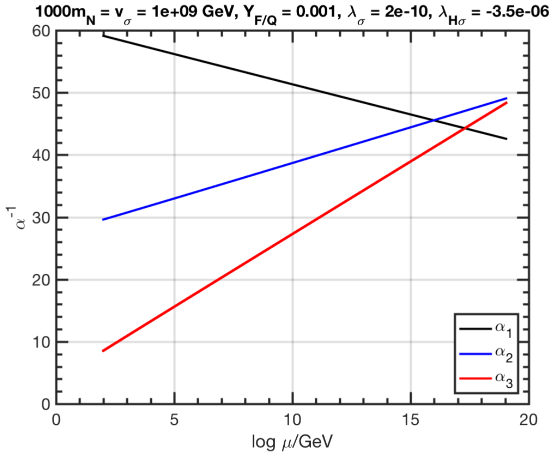
Y^F	10^{-3}
Y_N	0.0141
Y_Q	10^{-3}
λ_σ	5×10^{-9}
v_σ	10^{10} GeV

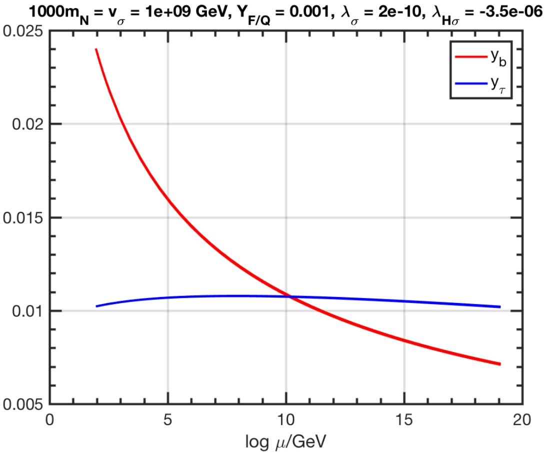
1. Two-loop corrections to β-functions produced by SARAH [Ballesteros, Redondo, Ringwald, Tamarit 1610.01639]
2. We solved numerically the 14 coupled renormalization group differential equations with respect to Yukawa $(Y^t, Y^b, Y^\tau, Y^F, Y^N, Y^Q)$, gauge (g_1, g_2, g_3) and scalar $(\mu_H, \mu_S, \lambda_H, \lambda_S, \lambda_{H\sigma})$ couplings, ignoring the light SM degrees of freedom
3. We used MATLAB's `ode45`-solver

No grand unification



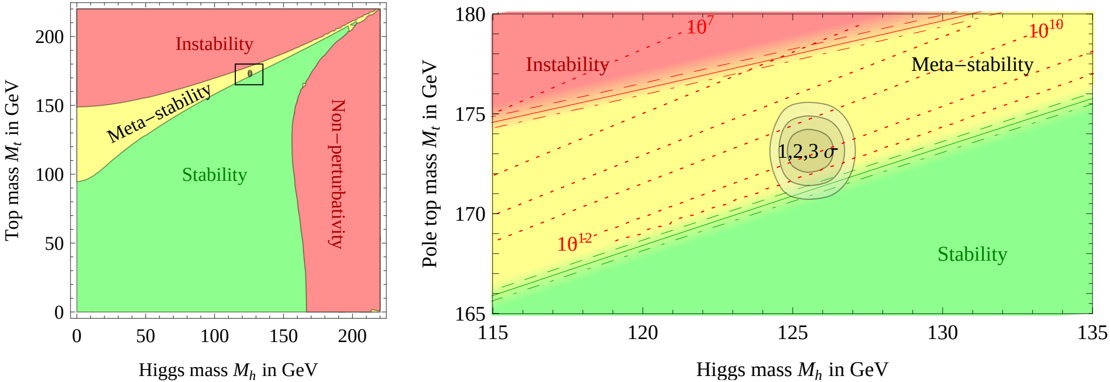
No grand unification





Brink of the abyss

The best-fit point for m_t and m_H implies that we live in a metastable world, however with very long vacuum decay timescale:



$$m_t = 172.44 \pm 0.60 \text{ GeV}, \quad m_H = 125.09 \pm 0.32 \text{ GeV}$$

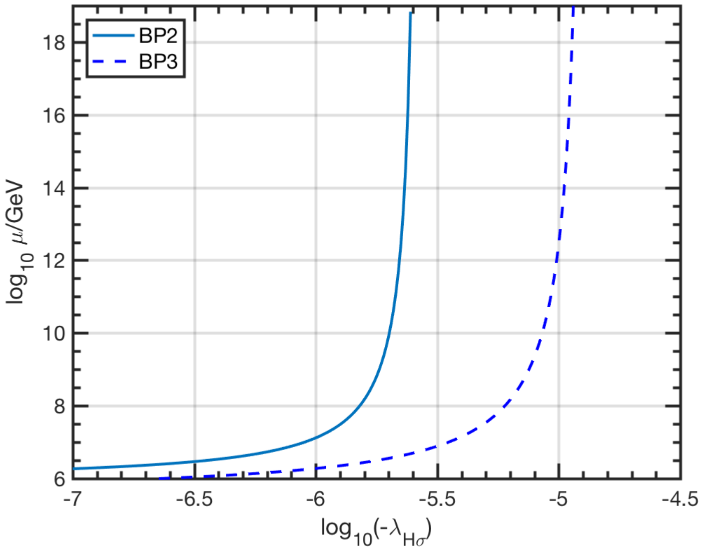
Metastability correlations

$$\beta_{\lambda_H} = \beta_{\lambda_H}^{SM} + \frac{1}{16\pi^2}\left[4\lambda_{H\sigma}^2 + 4\mathrm{Tr}[FF^\dagger]\lambda_H - 2\mathrm{Tr}\left[FF^\dagger FF^\dagger\right]\right] + \frac{1}{(16\pi^2)^2}\left[\frac{18}{125}g_1^4 q^2\left(25\lambda_H - 6g_1^2\right.\right.$$
$$\left. -10g_2^2\right) - 40\lambda_H\lambda_{H\sigma}^2 - 32\lambda_{H\sigma}^3 - 24y^2\lambda_{H\sigma}^2 + g_1^2\left(\frac{3\mathrm{Tr}[FF^\dagger]\lambda_H}{2} - \frac{3g_2^2\mathrm{Tr}[FF^\dagger]}{10}\right)$$
$$+ \frac{15}{2}g_2^2\mathrm{Tr}[FF^\dagger]\lambda_H - \frac{9g_1^4}{100}\mathrm{Tr}[FF^\dagger] - \frac{3g_2^4\mathrm{Tr}[FF^\dagger]}{4} - 14\mathrm{Tr}\left[GG^\dagger FF^\dagger\right]\lambda_H - 48\mathrm{Tr}[FF^\dagger]\lambda_H^2$$
$$- \mathrm{Tr}\left[FF^\dagger FF^\dagger\right]\lambda_H - 2\mathrm{Tr}\left[FF^\dagger GG^\dagger GG^\dagger\right] - 2\mathrm{Tr}\left[FF^\dagger FF^\dagger GG^\dagger\right] + 10\mathrm{Tr}\left[FF^\dagger FF^\dagger FF^\dagger\right]$$
$$\left. -3\mathrm{Tr}[Y^\dagger YF^\dagger F]\lambda_H - 4\mathrm{Tr}[Y^\dagger Y]\lambda_{H\sigma}^2 + 2\mathrm{Tr}[Y^\dagger F^t F^* YF^\dagger F] + 2\mathrm{Tr}[Y^\dagger YF^\dagger FF^\dagger F]\right],$$

A large value of $\lambda_{H\sigma}$ can give positive correction at one-loop level to push λ_H out of the valley of instability

The correlations of other SMASH parameters to λ_H are small

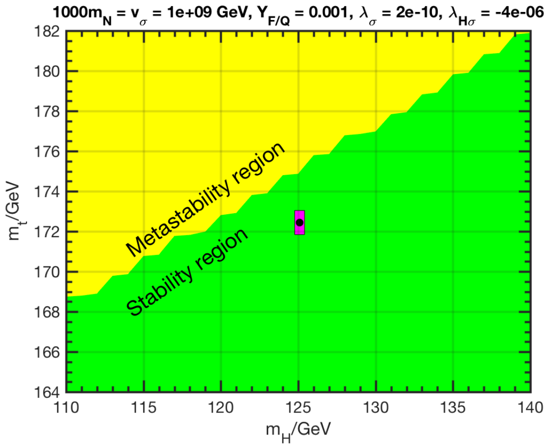
Turning on the portal coupling at two-loop level

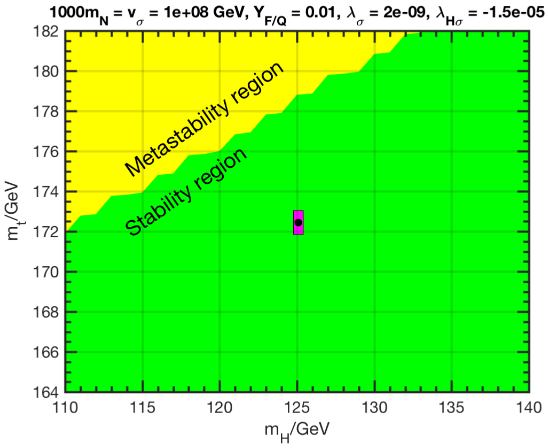


m_t = 172.44 GeV
m_H = 125.09 GeV

Metastability problem runs away upon the activation of $\lambda_{H\sigma}$

Scalar potential stability regions for $\lambda_{H\sigma} \approx -10^{-5}$



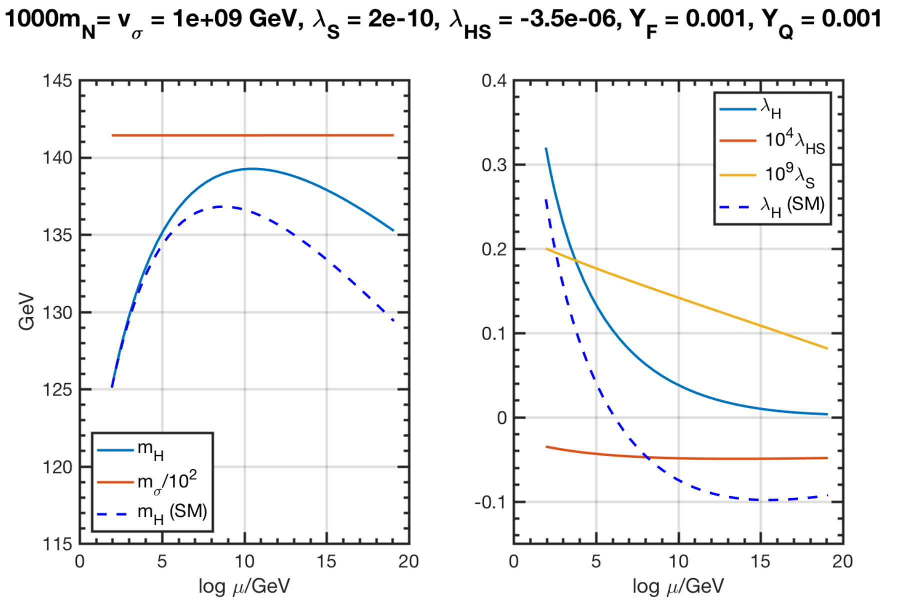


The Veltman condition: Str$\mathcal{M}^2$ = 0

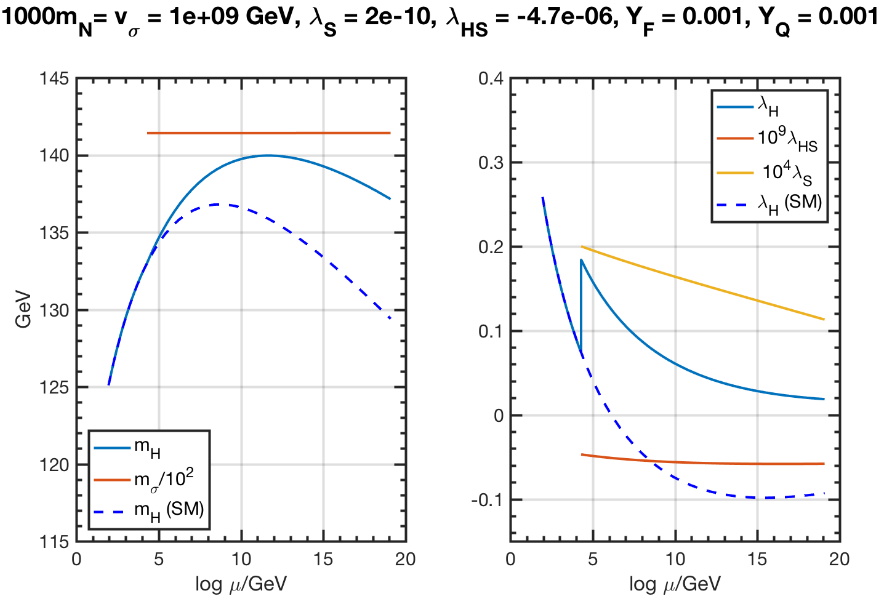
$$\beta_{\mu_H^2} = \beta_{\mu_H^2}^{SM} + \frac{1}{16\pi^2}\left[4\lambda_{H\sigma}\mu_\sigma^2 + 2\mathrm{Tr}[FF^\dagger]\mu_H^2\right] + \frac{1}{(16\pi^2)^2}\left[\frac{9}{5}g_1^4 q^2 \mu^2{}_H - \mu_\sigma^2\left(16\lambda_{H\sigma}^2 + 24y^2\lambda_{H\sigma}\right)\right.$$
$$- 4\mu_H^2\lambda_{H\sigma}^2 + \mu_H^2\left(\frac{3g_1^2\mathrm{Tr}[FF^\dagger]}{4} + \frac{15g_2^2\mathrm{Tr}[FF^\dagger]}{4} - 24\mathrm{Tr}[FF^\dagger]\lambda_H - 7\mathrm{Tr}\left[GG^\dagger FF^\dagger\right]\right.$$
$$\left.\left. - \frac{9\mathrm{Tr}\left[FF^\dagger FF^\dagger\right]}{2}\right) - \frac{3}{2}\mathrm{Tr}[Y^\dagger Y F^\dagger F]\mu_H^2 - 4\mathrm{Tr}[Y^\dagger Y]\lambda_{H\sigma}\mu_\sigma^2\right],$$

$$\beta_{\mu_\sigma^2} = \frac{1}{16\pi^2}\left[8\mu_H^2\lambda_{H\sigma} + \mu_\sigma^2\left(8\lambda_\sigma + 6y^2 + \mathrm{Tr}[Y^\dagger Y]\right)\right] + \frac{1}{(16\pi^2)^2}\left[\mu_H^2\left[\lambda_{H\sigma}\left(\frac{48g_1^2}{5} - 48y_b^2\right.\right.\right.$$
$$\left.\left. + 48g_2^2 - 48y_t^2\right) - 32\lambda_{H\sigma}^2\right] + \mu_\sigma^2\left(40g_3^2y^2 - 8\lambda_{H\sigma}^2 - 40\lambda_\sigma^2 - 9y^4 - 48y^2\lambda_\sigma\right) + 18g_1^2q^2y^2\mu^2{}_\sigma$$
$$-\mu_H^2\lambda_{H\sigma}(16\mathrm{Tr}[GG^\dagger] + 16\mathrm{Tr}[FF^\dagger]) - \mu_\sigma^2\left(\frac{3\,\mathrm{Tr}[YY^\dagger YY^\dagger]}{2} + 3\mathrm{Tr}[Y^\dagger Y F^\dagger F]\right.$$
$$\left.\left. + 8\mathrm{Tr}[Y^\dagger Y]\lambda_\sigma\right)\right],$$

Higgs and σ bare mass parameters: Threshold at m_Z



Higgs and σ bare mass parameters: Threshold at m_ρ



Conclusions

1. SMASH unifies axions, seesaw and extended Higgs sector on one energy scale, $\mu \sim 10^{10} - 10^{11}$ GeV, solving several problems badgering the Standard Model in one go.
2. SM vacuum is metastable, since λ_H turns negative around $\mu \simeq 10^{12}$ GeV, SMASH can fix this vacuum metastability problem with $\lambda_{H\sigma} \gtrsim -10^{-5}$ at two-loop RGE level.
3. Further investigations from cosmology part will fix the $\lambda_{H\sigma}$ value.