SMASH model and atmospheric neutrino mass splitting

C.R. Das

Bogoliubov Laboratory of Theoretical Physics (BLTP)
Joint Institute for Nuclear Research (JINR)
Dubna, Russian Federation

in collaboration with

Timo J. Kärkkäinen and Katri Huitu

Department of Physics, University of Helsinki, Finland

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Problems of the SM already have possible solutions

Biggest problems in physics (grand unification not included):

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

$$
\left|\begin{array}{c|cccc|c|cc|}
\text{Gen I} & u & d & e & \nu_e & & N_1 & Q \\
\text{Gen II} & c & s & \mu & \nu_\mu & & N_2 & \\
\text{Gen III} & t & b & \tau & \nu_\tau & + & N_3 & \\
\text{Gauge bosons} & g & W & Z & \gamma & & & \\
\text{Scalars} & & & & H & & A & \rho
\end{array}\right.
$$

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

1. Three heavy right-handed sterile Majorana neutrinos N_i
2. Colour triplets $Q \sim \mathbf{3}$ and $\tilde{Q} \sim \overline{\mathbf{3}}$
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:

$$
\begin{aligned}
-\mathcal{L}_{\text{Yukawa}} = {} & Y^u_{ij} q_{Li} \varepsilon H u_{Rj} + Y^d_{ij} q_{Li} H^\dagger d_{Rj} + G_{ij} L_{Li} H^\dagger \ell_{Rj} \\
& + \underbrace{Y^F_{ij} L_{Li} \varepsilon H N_j + \frac{1}{2} Y^N \sigma N_i N_j}_{\text{neutrino mass and leptogenesis}} \\
& + \underbrace{Y^Q \tilde{Q} \sigma Q + y^Q_i \sigma Q d_{Ri}}_{\text{strong CP problem}} + \text{ h.c.}
\end{aligned}
$$

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]

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

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

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]

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

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

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

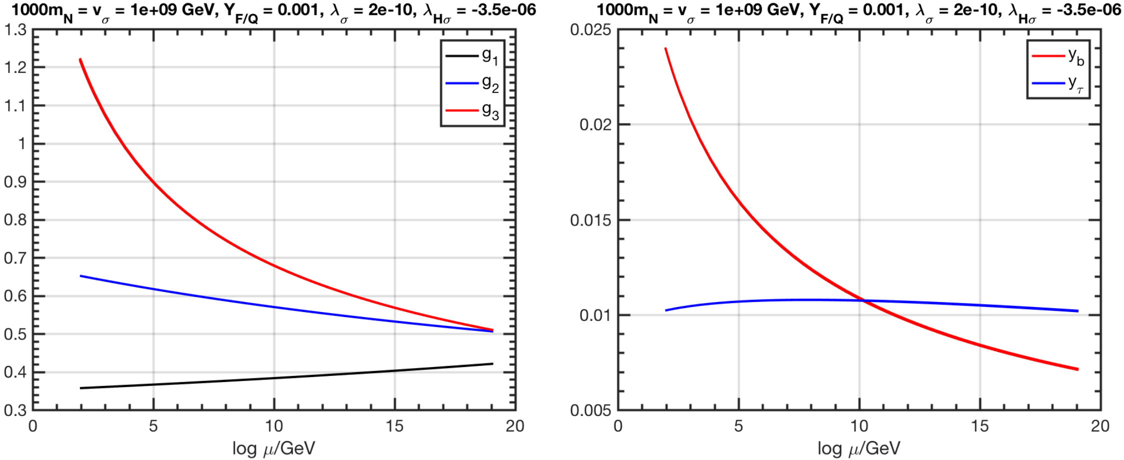
[Das, Kärkkäinen, Huitu 18XX.XXXX]

Benchmark point

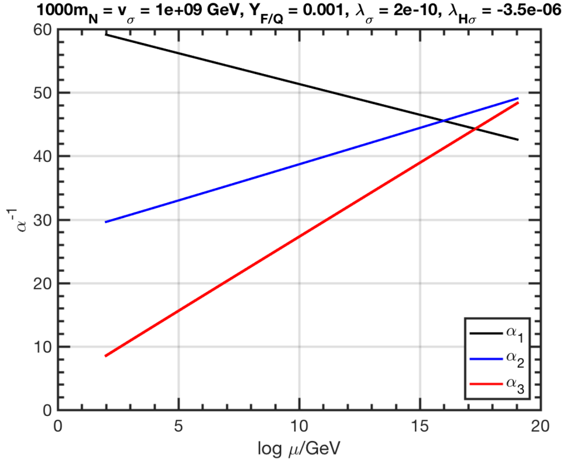
Y^F	10^{-3}
Y_N	0.0141
Y_Q	10^{-3}
λ_σ	5×10^{-9}
v_σ	10^{10} GeV

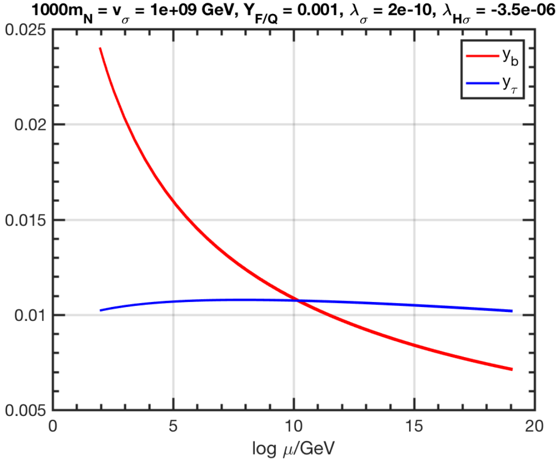
1. Two-loop corrections to β-functions produced by SARAH [Ballesteros, Redondo, Ringwald, Tamarit 1610.01639]
2. We solved numerically the 14 coupled renormalization group differential equations with respect to Yukawa $(Y^t, Y^b, Y^\tau, Y^F, Y^N, Y^Q)$, gauge (g_1, g_2, g_3) and scalar $(\mu_H, \mu_S,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

No grand unification



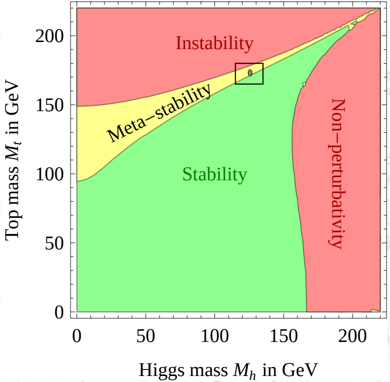
No grand unification

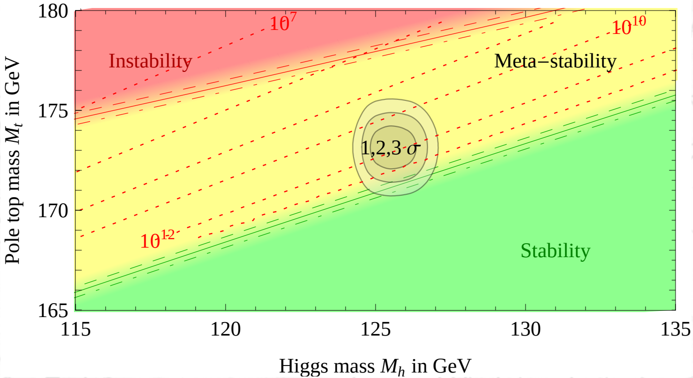




Brink of the abyss

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:





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

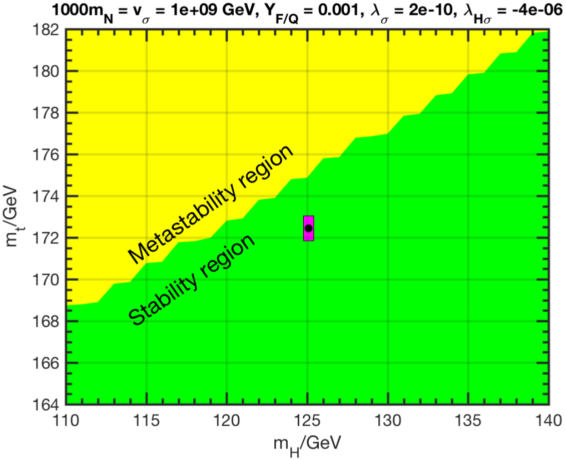
Metastability correlations

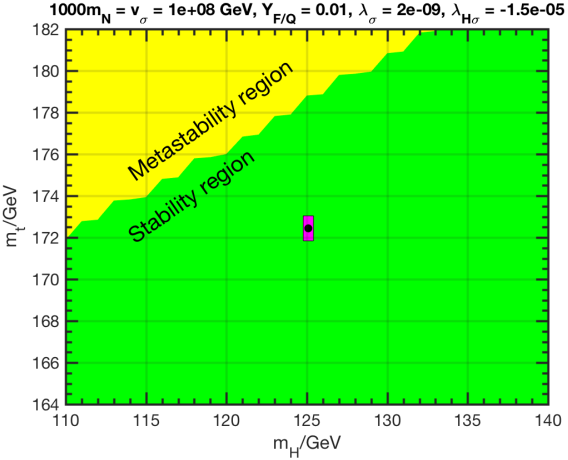
$$
\begin{aligned}
\beta_{\lambda_H} =& \beta_{\lambda_H}^{SM} + \frac{1}{16\pi^2}\left[4\lambda_{H\sigma}^2 + 4\mathrm{Tr}[FF^\dagger]\lambda_H - 2\mathrm{Tr}\left[FF^\dagger FF^\dagger\right]\right] + \frac{1}{(16\pi^2)^2}\left[\frac{18}{125}g_1^4 q^2\left(25\lambda_H - 6g_1^2\right.\right. \\
& \left.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

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

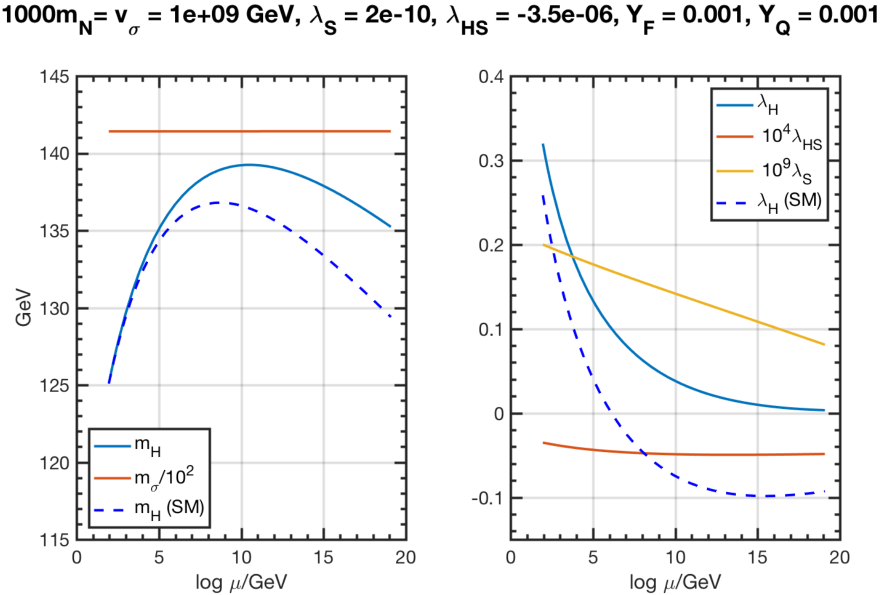
The correlations of other SMASH parameters to λ_H are small

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

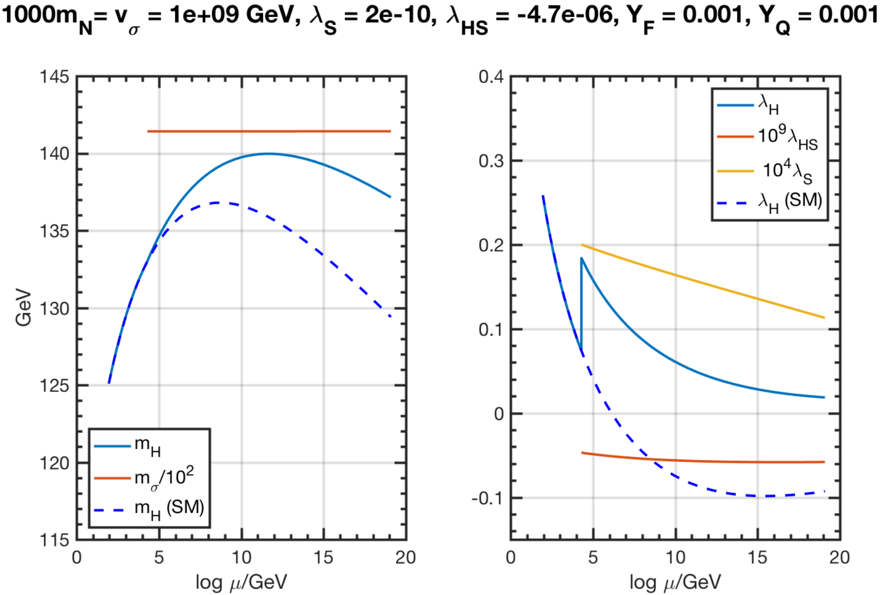




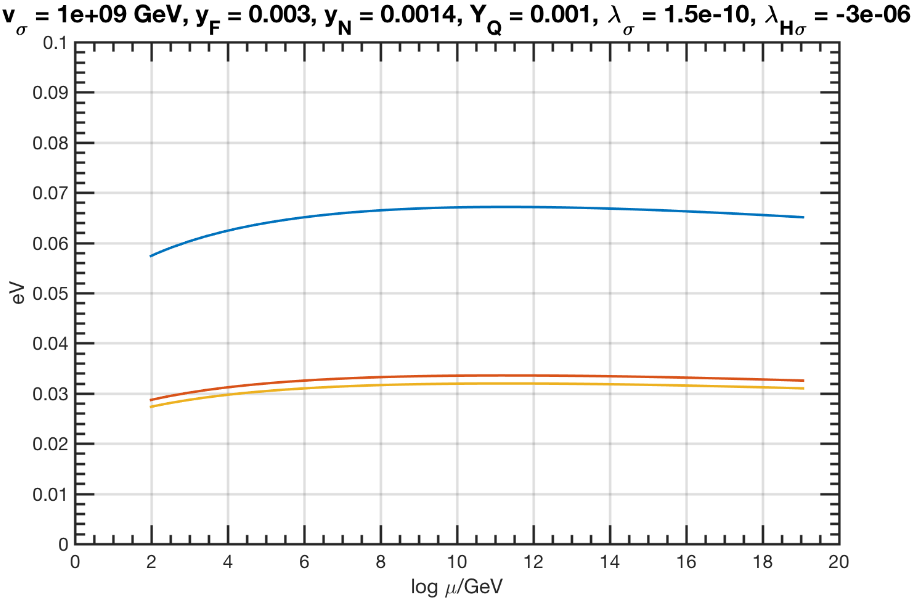
Higgs and σ bare mass parameters: Threshold at m_Z



Higgs and σ bare mass parameters: Threshold at m_ρ



Atmospheric neutrino mass splitting around 0.05 eV



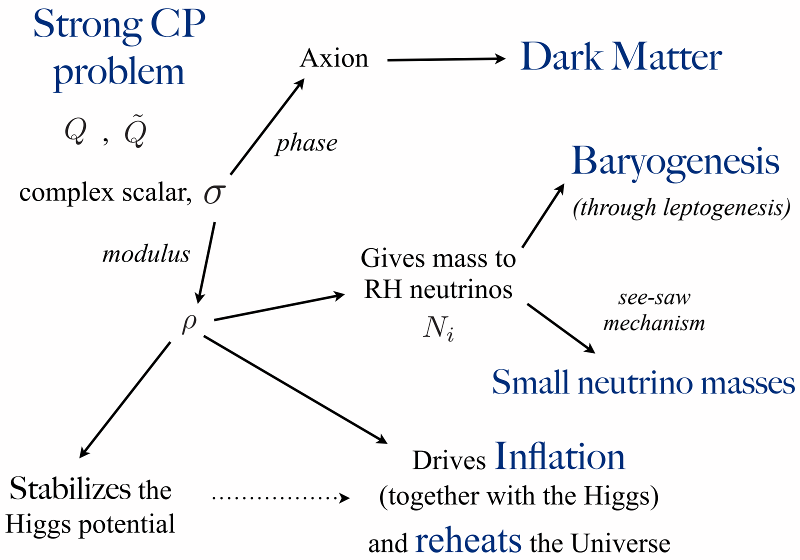
Conclusions

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. SMASH shows atmospheric neutrino mass splitting is around 0.05 eV and solar neutrino mass splitting is around 0.009 eV.

Testing SMASH

Further investigations from cosmology part will fix the $\lambda_{H\sigma}$ value:

- From measurements of the cosmic microwave background anisotropies (CMB) and large scale structures (LSS) of the Universe:
  Spectral index and running, tensor-to-scalar ratio, N_{eff}.
- Axion dark matter:
  Axion-photon coupling and mass.


Strong CP problem
Q , $\tilde{Q}$
complex scalar, σ
phase
Axion
Dark Matter
modulus
ρ
Gives mass to RH neutrinos
N_i
Baryogenesis
(through leptogenesis)
see-saw mechanism
Small neutrino masses
Stabilizes the Higgs potential
Drives Inflation
(together with the Higgs)
and reheats the Universe

Backup

10^{19} GeV — Planck mass

10^{11} GeV — Axion decay constant

$f_A = v_\sigma \quad \sim \quad$ SM instability scale Λ_I

VEV of new scalar

125 GeV — Higgs mass

~ 0.15 GeV — $\Lambda_{\rm QCD}$

10^{-13} GeV — Axion mass

Yukawa couplings and potential:

$$\mathcal{L} \supset -\Big[Y_{uij} q_i \epsilon H u_j + Y_{dij} q_i H^\dagger d_j + G_{ij} L_i H^\dagger E_j + \underbrace{F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j}_{\text{See-saw}}$$
$$\underbrace{+ y\, \tilde{Q} \sigma Q + y_{Q_{d}i} \sigma Q d_i + h.c.}_{\text{Strong CP problem (and DM)}} \Big] ,$$

$$V(H,\sigma) = \lambda_H \left(H^\dagger H - \frac{v^2}{2}\right)^2 + \underbrace{\lambda_\sigma \left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)^2}_{} + \underbrace{2\lambda_{H\sigma} \left(H^\dagger H - \frac{v^2}{2}\right)\left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)}_{\text{Stability, inflation and reheating}}$$

Couplings to gravity:

$$S \supset -\int d^4x \sqrt{-g}\, \left[\frac{M^2}{2} + \underbrace{\xi_H\, H^\dagger H + \xi_\sigma\, \sigma^* \sigma}_{\text{Inflation}}\right] R$$

After preheating: Reheating

A small Higgs component in the inflaton
of SMASH is crucial for successful reheating

Two possibilities:

$\lambda_{H\sigma} > 0$, $T_R \sim 10^7$ GeV

Axions remain decoupled
from thermal bath

$\Delta N_{\text{eff}} \sim 1$

Too much axion radiation

$\lambda_{H\sigma} < 0$, $T_R \sim 10^{10}$ GeV

$\Delta N_{\text{eff}} \sim 0.03$

✓

$N_\nu^{\text{eff}} = 3.04 \pm 0.18$

from CMB and BAO data