Inflating With A Superheavy Higgs in a SUSY Pati-Salam GUT

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Based on:

- C. Pallis and N. Toumbas, *J. Cosmol. Astropart. Phys.* **12**, *002 (2011)* [arXiv:1108.1771].

Outline

Coupling non-minimally the Inflaton to Gravity

• The Action Of A Scalar Field σ non-Minimally Coupled to the Ricci Scalar Curvature, $\mathcal{R}$, Through A Frame Function $f(\sigma)$ in the Jordan Frame (JF) is:

$$\mathcal{S}=\int d^4x\sqrt{-g}\left(-\frac{1}{2}m_{\rm P}^2f(\sigma)\mathcal{R}+\frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma-V(\sigma)\right),$$

where g is the Determinant Of The Background Friedmann-Robertson-Walker Metric and $f(\langle\sigma\rangle)\simeq 1$ to Recover Einstein Gravity At Low Energy. We can write S in the Einstein Frame (EF) as follows

$$\mathcal{S}=\int d^4x\sqrt{-\widehat{g}}\left(-\frac{1}{2}m_{\rm P}^2\widehat{\mathcal{R}}+\frac{1}{2}\widehat{g}^{\mu\nu}\partial_\mu\widehat{\sigma}\partial_\nu\widehat{\sigma}-\widehat{V}(\widehat{\sigma})\right)$$

• Performing a Conformal Transformation[1]:

We define the EF metric $\widehat{g}_{\mu\nu}=f\,g_{\mu\nu}\ \Rightarrow\ \begin{cases}\sqrt{-\widehat{g}}=f^2\sqrt{-g}\ \text{ and }\ \widehat{g}^{\mu\nu}=g^{\mu\nu}/f,\\ \widehat{\mathcal{R}}=\left(\mathcal{R}+3\Box\ln f+3g^{\mu\nu}\partial_\mu f\partial_\nu f/2f^2\right)/f\end{cases}$

and Introduce the EF Canonically Normalized Field, $\widehat{\sigma}$, and Potential, $\widehat{V}$, Defined As Follows:

$$\left(\frac{d\widehat{\sigma}}{d\sigma}\right)^2=J^2=\frac{1}{f}+\frac{3}{2}m_{\rm P}^2\left(\frac{f_{,\sigma}}{f}\right)^2\quad\text{and}\quad\widehat{V}(\widehat{\sigma})=\frac{V(\widehat{\sigma}(\sigma))}{f(\widehat{\sigma}(\sigma))^2},$$

• The Analysis of non-MI in the EF Using The Standard Slow-Roll Approximation is Equivalent[2] With The Analysis in JF.
• In These Theories σ Can Decay Via Gravitational Effects[3] Even Without Explicit Couplings Between σ and Matter Fields.

[1] K. Maeda (1989)
[2] D.S. Salopek, J.R. Bond and J.M. Bardeen (1989); D.I. Kaiser (1995); T. Chiba and M. Yamaguchi (2008).
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Inflationary Observables

- The Number of e-foldings, $\widehat{N}_*$, that the Scale $k_* = 0.002/\mathrm{Mpc}$ Suffers During non-MHI is

$$\widehat{N}_* = \frac{1}{m_{\rm P}^2}\int_{\widehat{\sigma}_{\rm f}}^{\widehat{\sigma}_*} d\widehat{\sigma}\,\frac{\widehat{V}}{\widehat{V}_{,\widehat{\sigma}}} = \frac{1}{m_{\rm P}^2}\int_{\sigma_{\rm f}}^{\sigma_*} d\sigma\, J^2\,\frac{\widehat{V}}{\widehat{V}_{,\sigma}},$$

Where σ_* $[\widehat{\sigma}_*]$ is The Value of σ $[\widehat{\sigma}]$ When k_* Crosses Outside The Inflationary Horizon; $\sigma_{\rm f}$ $[\widehat{\sigma}_{\rm f}]$ is the Value of σ $[\widehat{\sigma}]$ at the end of non-MI Which Can Be Found From The Condition

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- The Power Spectrum $P_{\mathcal{R}}$ of the Curvature Perturbations Generated by σ at the Pivot Scale k_* is Found by:

$$P_{\mathcal{R}}^{1/2} = \frac{1}{2\sqrt{3}\,\pi m_{\rm P}^3}\,\frac{\widehat{V}(\widehat{\sigma}_*)^{3/2}}{|\widehat{V}_{,\widehat{\sigma}}(\widehat{\sigma}_*)|} = \frac{|J(\sigma_*)|}{2\sqrt{3}\,\pi m_{\rm P}^3}\,\frac{\widehat{V}(\sigma_*)^{3/2}}{|\widehat{V}_{,\sigma}(\sigma_*)|}$$

And Can Be Normalized by WMAP7 Best Fit Value: $P_{\mathcal{R}} = 4.93\cdot 10^{-5}$.

- The (Scalar) Spectral Index, $n_{\rm s}$, Its Running, $a_{\rm s}$, And The Scalar-To-Tensor Ratio r Can Be Estimated As Follows:

$$n_{\rm s} = 1 - 6\widehat{\epsilon}_* + 2\widehat{\eta}_*, \quad \alpha_{\rm s} = \frac{2}{3}\left(4\widehat{\eta}_*^2 - (n_{\rm s}-1)^2\right) - 2\widehat{\xi}_* \quad \text{and} \quad r = 16\widehat{\epsilon}_*$$

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- We Have To Check The Hierarchy Between The Ultraviolet cut-off, Λ, of the Effective Theory And The Inflationary Scale.[4] In Particular, The Validity Of The Effective Theory Implies

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The Quartic Potential, $V = \lambda\sigma^4/4$

- If $f(\sigma) = 1$, i.e., With Minimal Coupling to Gravity. We Find:

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$$n_{\rm s} \simeq 1 - 3/\widehat{N}_* \simeq 0.947,\quad \alpha_{\rm s} \simeq -3/N_*^2 = 9.5\cdot 10^{-4} \text{ and } r \simeq 16/\widehat{N}_* \simeq 0.28$$ In Contradiction With Observations.

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- If $f(\sigma) = 1 + c_{\mathcal{R}}(\sigma/m_{\rm P})^2$, i.e., With the Standard non-Minimal Coupling to Gravity. We Find

$$\widehat{V} \simeq \frac{\lambda m_{\rm P}^4}{c_{\mathcal{R}}^2},\ \widehat{\epsilon} \simeq \frac{4m_{\rm P}^4}{3c_{\mathcal{R}}^2\sigma^4} \text{ and } \widehat{\eta} \simeq -\frac{4m_{\rm P}^2}{3c_{\mathcal{R}}\sigma^2} \text{ Therefore } \max\{\widehat{\epsilon}(\sigma_{\rm f}), |\widehat{\eta}(\sigma_{\rm f})|\} = 1 \Rightarrow \sigma_{\rm f} = \sqrt[4]{\frac{4}{3}}\frac{m_{\rm P}}{\sqrt{c_{\mathcal{R}}}} \text{ and}$$

$$\widehat{N}_* \simeq \frac{3c_{\mathcal{R}}\sigma_*^2}{4m_{\rm P}^2} \Rightarrow \sigma_* = 2m_{\rm P}\sqrt{\frac{\widehat{N}_*}{3c_{\mathcal{R}}}}\cdot \text{ Also } P_{\mathcal{R}}^{1/2} \simeq \frac{\sqrt{\lambda}\widehat{N}_*}{6\sqrt{2}\pi c_{\mathcal{R}}} = 4.93\cdot 10^{-5} \Rightarrow \underline{c_{\mathcal{R}} \simeq 41850\sqrt{\lambda}} \text{ for } \widehat{N}_* \simeq 55$$

$n_{\rm s} \simeq 1-2/\widehat{N}_* \simeq 0.965,\ \alpha_{\rm s} \simeq -2/\widehat{N}_*^2 \simeq -6.4\cdot 10^{-4}$ and $r \simeq 12/\widehat{N}_*^2 \simeq 4\cdot 10^{-3}$ In Excellent Agreement With Observations

Shortcomings of non-SUSY non-MHI

- The Hierarchy Problem Within GUTs Is Not Solved;
- The Generation Of The Observed Baryon Asymmetry Of The Universe (BAU) And The Existence Of Tiny But Non-Zero Neutrino Masses and the Dark Matter Are Not Explained;
- As Regards The non-Minimal Higgs Inflation (non-MHI) Within Standard Model (SM) the Required Mass of Higgs Field Seems To Be Heavier Than The Recently Announced LHC Results and the Reheating Process[5] Is Rather Complicate.

[5] J. Garcia-Bellido, D.G. Figueroa and J. Rubio (2008); F. Bezrukov, D. Gorbunov and M. Shaposhnikov (2009)

Non-Minimal Inflation in SUGRA

- The General EF Action For The Scalar Fields ϕ^α Plus Gravity In Four Dimensional, $\mathcal{N}=1$ SUGRA is:

$$\mathcal{S}=\int d^4x\sqrt{-\widehat{g}}\left(-\frac{1}{2}m_{\rm P}^2\widehat{\mathcal{R}}+K_{\alpha\bar\beta}\widehat{g}^{\mu\nu}D_\mu\phi^\alpha D_\nu\phi^{*\bar\beta}-\widehat{V}_{\rm F}+\widehat{V}_{\rm D}\right),\quad \text{Where}\quad K_{\alpha\bar\beta}=\frac{\partial^2K}{\partial\phi^\alpha\partial\phi^{*\bar\beta}}>0,\quad K^{\bar\beta\alpha}K_{\alpha\bar\gamma}=\delta^{\bar\beta}_{\bar\gamma}$$

$$\widehat{V}_{\rm F}=e^{K/m_{\rm P}^2}\left(K^{\alpha\bar\beta}F_\alpha F_{\bar\beta}-3\frac{|W|^2}{m_{\rm P}^2}\right)\ \text{with}\ F_\alpha=W_{,\phi^\alpha}+K_{,\phi^\alpha}W/m_{\rm P}^2;\ \text{and}\ \widehat{V}_{\rm D}=\frac{1}{2}g^2D_aD_a\ \text{with}\ D_a=\phi_\alpha\left(T_a\right)^\alpha_{\bar\beta}K^{\bar\beta}$$

- In JF, $\mathcal{S}$ Can Exhibit Non-Minimal Couplings of ϕ^α's to $\mathcal{R}$ If We Adopt [6] $\Omega=-3e^{-K/3m_{\rm P}^2}\Rightarrow K=-3m_{\rm P}^2\ln\left(-\Omega/3\right)$,

$$\Omega=-3+\delta_{\alpha\bar\beta}\frac{\phi^\alpha\phi^{*\bar\beta}}{m_{\rm P}^2}-3\Big({\rm F}(\phi^\alpha)+{\rm F}^*(\phi^{*\bar\alpha})\Big)\Rightarrow K=-3m_{\rm P}^2\ln\left(1-\frac{1}{3m_{\rm P}^2}\delta_{\alpha\bar\beta}\phi^\alpha\phi^{*\bar\beta}+\Big({\rm F}(\phi^\alpha)+{\rm F}^*(\phi^{*\bar\alpha})\Big)\right).$$

Where F is a Dimensionless, Holomorphic Function.

- If We Take $W=S\,w(\phi)+\cdots$ with $\phi=\sigma/\sqrt{2}$ And Stabilize $S=0$, $\mathcal{S}$ Takes A Form Similar To The non-SUSY Case

$$\mathcal{S}=\int d^4x\sqrt{-g}\left(\frac{m_{\rm P}^2}{6}\mathcal{R}\left(1-\frac{\sigma^2}{6m_{\rm P}^2}+2{\rm F}(\sigma)\right)+\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma-V+\cdots\right)\quad \text{with}\quad V=\sum_a\left|W_{,\phi^\alpha}\right|^2+\frac{g^2}{2}\left(\sum_a\phi^{*\alpha}T^a_{\alpha\bar\beta}\phi^{\bar\beta}\right)$$

If $V_{\rm D}=0$ The EF Scalar Potential is $\widehat{V}=V_{\rm F}/f(\sigma)^2$ with $f(\sigma)=1-\sigma^2/6m_{\rm P}^2+2{\rm F}(\sigma)$

- Therefore, To Produce A Quartic F-Term Scalar Potential, We Need A Superpotential Of The Form:

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For $M<m_{\rm P}$ and $|\bar\Phi|=|\Phi|=h/2$ Entailed By A D-Flatness Condition, We Obtain

$$V_{\rm F}(S=0)\propto\lambda^2h^4/16\quad \text{and}\quad \widehat{V}=V_{\rm F}(S=0)/f(h)^2\quad \text{With}\quad f(h)\simeq1+c_{\mathcal{R}}(h/m_{\rm P})^2\quad \text{Therefore}\quad \widehat{V}={\rm cst}\ \text{for}\ c_{\mathcal{R}}\gg1.$$

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[6] M.B. Einhorn and D.R.T. Jones (2010); S. Ferrara, R. Kallosh, A. Linde, A. Marrani and A. Van Proeyen (2010, 2011); H.M. Lee (2010).

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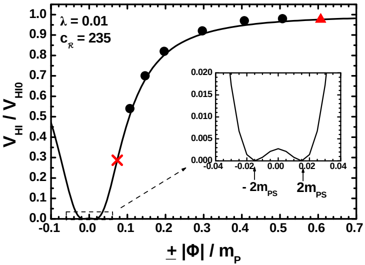
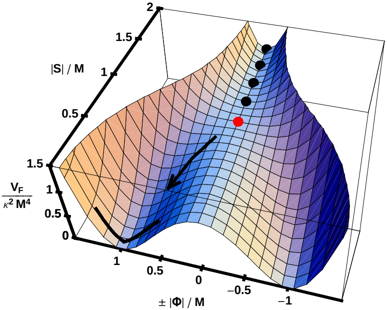
Comparing non-MHI and F-term Hybrid Inflation (FHI)

Non-Minimal Higgs Inflation



Standard F-term Hybrid Inflation



In Both Cases:

- We Need The Same Superpotential Terms and, Consequently We Have to Impose the Same R-Symmetry;
- The Flat Inflationary Trajectory Is Generated By Freezing Some Fields To Zero;
- Inflaton Can Decay Into Light Degrees Of Freedom Due To Non-Renormalizable Interaction Terms Arising[7] In The SUGRA Langrangian And Due To The Non-Vanishing Vacuum Expectation Value (VEV) of Infaton.

[7] M. Endo, M. Kawasaki, F. Takahashi and T.T. Yanagida (2006); M. Endo, F. Takahashi and T.T. Yanagida (2007).

Differences of non-MHI and FHI

Non-Minimal Higgs Inflation

- The Radial Part of the Higgs Field Drives Inflation;
- The GUT Symmetry is Broken during non-MHI ;
- No Cosmological Defects Are Produced;
- The GUT Scale Can Assume its SUSY value;
- The Flatness Of The Potential Arises Within SUGRA;
- non-MHI is Largely Independent From Radiative Corrections;
- The Inflationary Observables Lie Within The Range Of The Current Data;
- Possible Naturalness Problem With The Effective Theory.
- Possible Complications in the Reheating Process Occur Due to Instant Preheating[9].

Standard F-term Hybrid Inflation

- A Singlet Field Drives Inflation;
- The GUT Symmetry is Broken In The End of FHI;
- Cosmological Defects May Be Produced;
- The GUT Scale Turns Out To Be Mostly Lower Than Its SUSY value;
- The Flatness Of The Potential Arises Within SUSY;
- FHI Dependents Crucially On Radiative Corrections;
- The Spectral Index Lies Mostly Above The Range Of The Current Data;
- No Naturalness Problem With The Effective Theory;
- Possible Complications In The Reheating Process Occur Due To Tachyonic Preheating[10].

- We Below Analyze A Model Of non-MHI Within a SUSY Pati-Salam (PS) Gauge Group $G_{PS} = SU(4)_C \times SU(2)_L \times SU(2)_R$ Which Does Not Leads To Magnetic Monopoles During the Spontaneous Symmetry Breaking (SSB) To the SM one, $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$.

[9] G.N. Felder, L. Kofman and A.D. Linde (1999).
[10] Juan García-Bellido and Ester Ruiz Morales (2002).

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Super-fields	Represe-ntations under $G_{\rm PS}$	Decompo-sitions under $G_{\rm SM}$	Global Charges R	PQ	$\mathbb{Z}_2^{\rm mp}$
Matter Superfields					
F_i	$(\mathbf{4},\mathbf{2},\mathbf{1})$	$Q_{i{\rm a}}(\mathbf{3},\mathbf{2},1/6)$	1	-1	1
		$L_i(\mathbf{1},\mathbf{2},-1/2)$			
F^c_i	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	$u^c_{i{\rm a}}(\bar{\mathbf{3}},\mathbf{1},-2/3)$	1	0	-1
		$d^c_{i{\rm a}}(\bar{\mathbf{3}},\mathbf{1},1/3)$			
		$\nu^c_i(\mathbf{1},\mathbf{1},0)$			
		$e^c_i(\mathbf{1},\mathbf{1},1)$			
Higgs Superfields					
H^c	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	$u^c_{H{\rm a}}(\bar{\mathbf{3}},\mathbf{1},-2/3)$	0	0	0
		$d^c_{H{\rm a}}(\bar{\mathbf{3}},\mathbf{1},1/3)$			
		$\nu^c_H(\mathbf{1},\mathbf{1},0)$			
		$e^c_H(\mathbf{1},\mathbf{1},1)$			
$\bar{H}^c$	$(\mathbf{4},\mathbf{1},\mathbf{2})$	$\bar{u}^c_{H{\rm a}}(\mathbf{3},\mathbf{1},2/3)$	0	0	0
		$\bar{d}^c_{H{\rm a}}(\mathbf{3},\mathbf{1},-1/3)$			
		$\bar{\nu}^c_H(\mathbf{1},\mathbf{1},0)$			
		$\bar{e}^c_H(\mathbf{1},\mathbf{1},-1)$			
S	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$S(\mathbf{1},\mathbf{1},0)$	2	0	0
G	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$\bar{g}^c_{\rm a}(\mathbf{3},\mathbf{1},-1/3)$	2	0	0
		$g^c_{\rm a}(\bar{\mathbf{3}},\mathbf{1},1/3)$			
H	$(\mathbf{1},\mathbf{2},\mathbf{2})$	$H_u(\mathbf{1},\mathbf{2},1/2)$	0	1	0
		$H_d(\mathbf{1},\mathbf{2},-1/2)$			
P	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$P(\mathbf{1},\mathbf{1},0)$	1	-1	0
$\bar{P}$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$\bar{P}(\mathbf{1},\mathbf{1},0)$	0	1	0

The Relevant Superpotential

We Focus on the PS and PQ-invariant Superpotential

$$W = W_{\rm MSSM} + W_{\rm PQ} + W_{\rm HPS} \quad \text{Where}$$

- $W_{\rm MSSM} = y_{ij}F_i\mathsf{H}F^c_j = y_{ij}F_i\left(H_u \quad H_d\right)F^c_j =$

$$y_{ij}\left({H_d}^{\mathsf{T}}\varepsilon L_i e^c_j - {H_u}^{\mathsf{T}}\varepsilon L_i\nu^c_j + {H_d}^{\mathsf{T}}\varepsilon Q_{i{\rm a}}d^c_{j{\rm a}} - {H_u}^{\mathsf{T}}\varepsilon Q_{i{\rm a}}u^c_{j{\rm a}}\right),$$

with $\varepsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0\end{pmatrix}$, $Q_{i{\rm a}} = \begin{pmatrix} u_{i{\rm a}} \\ d_{i{\rm a}}\end{pmatrix}$ and $L_i = \begin{pmatrix} \nu_i \\ e_i\end{pmatrix}$.

- $$W_{\rm PQ} = \lambda_{\rm PQ}\frac{P^2\bar{P}^2}{M_{\rm S}} - \underbrace{\lambda_\mu\frac{P^2}{2M_{\rm S}}{\rm Tr}\left(\mathsf{H}\varepsilon\mathsf{H}^{\mathsf{T}}\varepsilon\right)}_{\text{to Generate } \mu = \lambda_\mu f_a^2/M_{\rm S} \sim 1\ {\rm TeV}},$$

- $$W_{\rm HPS} = \lambda S\left(\bar{H}^c H^c - M^2_{\rm PS}\right) + \underbrace{\lambda_{i\nu^c}\frac{\left(\bar{H}^c F^c_i\right)^2}{M_{\rm S}}}_{\text{to Generate Masses for RHNs}}$$
$$+ \underbrace{\lambda_H {H^c}^{\mathsf{T}} G\varepsilon H^c + \lambda_{\bar{H}}\bar{H}^c\bar{G}\varepsilon{\bar{H}^{c\,\mathsf{T}}}}_{\text{to Generate Masses for } d^c_H,\ \bar{d}^c_H}$$

with $G = \begin{pmatrix} \varepsilon_{\rm abc}g^c_{\rm c} & \bar{g}^c_{\rm a} \\ -\bar{g}^c_{\rm a} & 0\end{pmatrix} \Rightarrow \bar{G} = \begin{pmatrix} \varepsilon_{\rm abc}\bar{g}^c_{\rm c} & g^c_{\rm a} \\ -g^c_{\rm a} & 0\end{pmatrix}$

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F_i^c	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	$u^c_{ia}(\bar{\mathbf{3}},\mathbf{1},-2/3)$	1	0	−1
		$d^c_{ia}(\bar{\mathbf{3}},\mathbf{1},1/3)$			
		$\nu^c_i(\mathbf{1},\mathbf{1},0)$			
		$e^c_i(\mathbf{1},\mathbf{1},1)$			
		Higgs Superfields			
H^c	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	$u^c_{Ha}(\bar{\mathbf{3}},\mathbf{1},-2/3)$	0	0	0
		$d^c_{Ha}(\bar{\mathbf{3}},\mathbf{1},1/3)$			
		$\nu^c_H(\mathbf{1},\mathbf{1},0)$			
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$\bar{H}^c$	$(\mathbf{4},\mathbf{1},\mathbf{2})$	$\bar{u}^c_{Ha}(\mathbf{3},\mathbf{1},2/3)$	0	0	0
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$$y_{ij}\left({H_d}^{\mathsf{T}}\varepsilon L_i e^c_j - {H_u}^{\mathsf{T}}\varepsilon L_i\nu^c_j + {H_d}^{\mathsf{T}}\varepsilon Q_{ia}d^c_{ja} - {H_u}^{\mathsf{T}}\varepsilon Q_{ia}u^c_{ja}\right),$$

with $\varepsilon = \begin{pmatrix}0 & 1\\ -1 & 0\end{pmatrix}$, $Q_{ia} = \begin{pmatrix}u_{ia}\\ d_{ia}\end{pmatrix}$ and $L_i = \begin{pmatrix}\nu_i\\ e_i\end{pmatrix}$.

- $$W_{\rm PQ} = \lambda_{\rm PQ}\frac{P^2\bar{P}^2}{M_{\rm S}} - \underbrace{\lambda_\mu\frac{P^2}{2M_{\rm S}}\mathrm{Tr}\left(\mathsf{H}\varepsilon\mathsf{H}^{\mathsf{T}}\varepsilon\right)}_{},$$

  to Generate $\mu = \lambda_\mu f_a^2/M_{\rm S} \sim 1$ TeV

- $$W_{\rm HPS} = \lambda S\left(\bar{H}^cH^c - M^2_{\rm PS}\right) + \underbrace{\lambda_{i\nu^c}\frac{\left(\bar{H}^cF^c_i\right)^2}{M_{\rm S}}}_{}$$

  to Generate Masses for RHNs

  $$+ \underbrace{\lambda_H {H^c}^{\mathsf{T}}G\varepsilon H^c + \lambda_{\bar{H}}\bar{H}^c\bar{G}\varepsilon{\bar{H}^c}{}^{\mathsf{T}}}_{}$$

  to Generate Masses for $d^c_H, \bar{d}^c_H$

with $G = \begin{pmatrix}\varepsilon_{\rm abc}g^c_{\rm c} & \bar{g}^c_{\rm a}\\ -\bar{g}^c_{\rm a} & 0\end{pmatrix} \Rightarrow \bar{G} = \begin{pmatrix}\varepsilon_{\rm abc}\bar{g}^c_{\rm c} & g^c_{\rm a}\\ -g^c_{\rm a} & 0\end{pmatrix}$

$W_{\rm HPS}$ In Terms Of The Components Of The Various Superfields Can Be Expressed As

$$\begin{aligned} W_{\rm HPS} &= \lambda S\left(\nu^c_H\bar\nu^c_H + e^c_H\bar e^c_H + u^c_H\bar u^c_H + d^c_H\bar d^c_H - M^2_{\rm PS}\right) + \lambda_{i\nu^c}\left(\bar e^c_H e^c_i + \bar d^c_H d^c_i - \bar\nu^c_H\nu^c_i - \bar u^c_H u^c_i\right)^2/M_{\rm S} \\ &- 2\lambda_H\left(\nu^c_H d^c_H - e^c_H u^c_H\right)\bar g^c + 2\lambda_H u^c_H d^c_H g^c - 2\lambda_{\bar H}\left(\bar\nu^c_H\bar d^c_H - \bar e^c_H\bar u^c_H\right)g^c + 2\lambda_{\bar H}\bar u^c_H\bar d^c_H\bar g^c \end{aligned}$$

The Relevant Kälher Potential

The Implementation Of non-MHI Within SUGRA Requires The Adoption The KÄhler Potential, K, As Follows

$$K = -3m^2_{\rm P}\ln\left(1 - \frac{\phi^\alpha\phi^{*\alpha}}{3m^2_{\rm P}} + k_S\frac{|S|^4}{3m^4_{\rm P}} + \frac{k_H}{2m^2_{\rm P}}\left(\nu^c_H\bar\nu^c_H + e^c_H\bar e^c_H + u^c_H\bar u^c_H + d^c_H\bar d^c_H + {\rm h.c.}\right)\right)$$

With $\phi^\alpha = \nu^c_H, \bar\nu^c_H, e^c_H, \bar e^c_H, u^c_H, \bar u^c_H, d^c_H, \bar d^c_H, g^c, \bar g^c, S$ and Summation Over The Repeated Greek Indices – e.g. α and $\bar\beta$ – is Implied.

- $k_S \neq 0$ is Necessitated in Order to Stabilize S.

The SUSY Potential

In The Limit Where $m_{\rm P}\to\infty$, $V_{\rm SUGRA}$ tends to its SUSY Limit, $V_{\rm SUSY}$. Assuming that the SM non-Singlet Components Vanish, We Find $V_{\rm SUSY} = V_{\rm F} + V_{\rm D}$ With

$$V_{\rm F} = \lambda^2\left|\bar\nu^c_H\nu^c_H - M^2_{\rm PS}\right|^2 + \lambda^2|S|^2\left(|\nu^c_H|^2 + |\bar\nu^c_H|^2\right) \quad \text{And} \quad V_{\rm D} = \frac{g^2}{8}\left[\frac{3}{2}\left(|\nu^c_H|^2 - |\bar\nu^c_H|^2\right)^2 + \left(|\bar\nu^c_H|^2 - |\nu^c_H|^2\right)^2\right]$$

The SUSY Vacuum Can Be Found Lies From The Conditions

$$V_{\rm D} = 0 \quad\Leftrightarrow\quad |\nu^c_H| = |\bar\nu^c_H|$$

$$V_{\rm F} = 0 \quad\Leftrightarrow\quad \langle S\rangle \simeq 0 \ \text{ and } \ \left|\langle\nu^c_H\rangle\right| = \left|\langle\bar\nu^c_H\rangle\right| = M_{\rm PS}.$$

Therefore, $G_{\rm PS}\times U(1)_{\rm PQ}$ is Spontaneously Broken Down to $G_{\rm SM}\times\mathbb{Z}_2$.

- The Same $V_{\rm F}$ Gives Also Rise to a Stage of non-MHI as We Show in the Following.

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$$\begin{aligned} W_{\rm HPS} &= \lambda S\left(\nu^c_H\bar\nu^c_H+e^c_H\bar e^c_H+u^c_H\bar u^c_H+d^c_H\bar d^c_H-M_{\rm PS}^2\right)+\lambda_{i\nu^c}\left(\bar e^c_He^c_i+\bar d^c_Hd^c_i-\bar\nu^c_H\nu^c_i-\bar u^c_Hu^c_i\right)^2/M_{\rm S}\\ &- 2\lambda_H\left(\nu^c_Hd^c_H-e^c_Hu^c_H\right)\bar g^c+2\lambda_Hu^c_Hd^c_Hg^c-2\lambda_{\bar H}\left(\bar\nu^c_H\bar d^c_H-\bar e^c_H\bar u^c_H\right)g^c+2\lambda_{\bar H}\bar u^c_H\bar d^c_H\bar g^c\end{aligned}$$

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With $\phi^\alpha=\nu^c_H,\bar\nu^c_H,e^c_H,\bar e^c_H,u^c_H,\bar u^c_H,d^c_H,\bar d^c_H,g^c,\bar g^c,S$ and Summation Over The Repeated Greek Indices – e.g. α and $\bar\beta$ – is Implied.

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The SUSY Vacuum Can Be Found Lies From The Conditions

$$V_{\rm D}=0\quad\Leftrightarrow\quad|\nu^c_H|=|\bar\nu^c_H|$$

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With $\phi^\alpha=\nu^c_H,\bar\nu^c_H,e^c_H,\bar e^c_H,u^c_H,\bar u^c_H,d^c_H,\bar d^c_H,g^c,\bar g^c,S$ and Summation Over The Repeated Greek Indices – e.g. α and $\bar\beta$ – is Implied.

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$$V_{\rm F}=\lambda^2\left|\bar\nu^c_H\nu^c_H-M^2_{\rm PS}\right|^2+\lambda^2|S|^2\left(|\nu^c_H|^2+|\bar\nu^c_H|^2\right)\quad\text{And}\quad V_{\rm D}=\frac{g^2}{8}\left[\frac{3}{2}\left(|\nu^c_H|^2-|\bar\nu^c_H|^2\right)^2+\left(|\bar\nu^c_H|^2-|\nu^c_H|^2\right)^2\right]$$

The SUSY Vacuum Can Be Found Lies From The Conditions

$$V_{\rm D}=0\quad\Leftrightarrow\quad|\nu^c_H|=|\bar\nu^c_H|$$

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- The Same $V_{\rm F}$ Gives Also Rise to a Stage of non-MHI as We Show in the Following.

The D-Flat Direction of the SUGRA Potential

- If We Use The Parameterization: $\boxed{\nu^c_H = he^{i\theta}\cos\theta_\nu/\sqrt{2} \;\; \text{and} \;\; \bar{\nu}^c_H = he^{i\bar{\theta}}\sin\theta_\nu/\sqrt{2}}$ Where h is the Inflaton,

We Can Easily Deduce From That a D-flat Direction Occurs At

$$\theta = \bar{\theta} = 0,\ \theta_\nu = \pi/4 \;\; \text{and} \;\; e^c_H = \bar{e}^c_H = u^c_H = \bar{u}^c_H = d^c_H = \bar{d}^c_H = g^c = \bar{g}^c = 0.$$

- Along this Direction, $V_{\rm HD}$ Vanishes And so, $V_{\rm HI} = \widehat{V}_{\rm HF}$ takes the form

$$V_{\rm HI0} = m_{\rm P}^4 \frac{\lambda^2 (x_h^2 - 4m_{\rm PS}^2)^2}{16 f^2} \;\; \text{with} \;\; f = 1 + c_{\mathcal{R}} x_h^2,\;\; m_{\rm PS} = \frac{M_{\rm PS}}{m_{\rm P}},\;\; x_h = \frac{h}{m_{\rm P}} \;\; \text{and} \;\; c_{\mathcal{R}} = -\frac{1}{6} + \frac{k_H}{4}.$$

- For $c_{\mathcal{R}} \gg 1$, $V_{\rm HI0}$ and the Corresponding Hubble Parameter $\widehat{H}_{\rm HI0}$ Become Almost Constant And Are Given By

$$V_{\rm HI0} = \frac{\lambda^2 h^4}{16 f^2} \simeq \frac{\lambda^2 m_{\rm P}^4}{16 c_{\mathcal{R}}^2} \;\; \text{and} \;\; \widehat{H}_{\rm HI0} = \frac{V_{\rm HI0}^{1/2}}{\sqrt{3} m_{\rm P}} \simeq \frac{\lambda m_{\rm P}}{4\sqrt{3} c_{\mathcal{R}}}\,.$$

- We Introduce the EF Canonically Normalized Fields, $\widehat{h}, \widehat{\theta}_+, \widehat{\theta}_-, \widehat{\theta}_\nu$ and $\widehat{\chi}$, as follows:

$$\frac{d\widehat{h}}{dh} = J = \sqrt{\frac{1}{f} + \frac{6c_{\mathcal{R}}^2 x_h^2}{f^2}},\;\; \widehat{\theta}_+ = \frac{Jh\theta_+}{\sqrt{2}},\;\; \widehat{\theta}_- = \frac{h\theta_-}{\sqrt{2f}},\;\; \widehat{\theta}_\nu = \frac{h\theta_\nu}{\sqrt{f}} \;\; \text{and} \;\; \widehat{\chi} = \frac{\chi}{\sqrt{f}}.$$

Where $\chi = S, x_1, x_2, \bar{x}_1$ and $\bar{x}_2$ Are The Fluctuations Of The Various Fields. We Expand Them In Real And Imaginary Parts As Follows $X = (x_1 + ix_2)/\sqrt{2},\;\; \bar{X} = (\bar{x}_1 + i\bar{x}_2)/\sqrt{2}$ where $X = e^c_H, u^c_H, d^c_H, g^c$ and $x = e, u, d, g$.

Therefore The Action Takes The Form

$$\mathsf{S}_{\rm HI} = \int d^4x \sqrt{-\widehat{\mathfrak{g}}}\left(-\frac{1}{2} m_{\rm P}^2 \widehat{\mathcal{R}} + \frac{1}{2}\widehat{\mathfrak{g}}^{\mu\nu} \sum_\phi \partial_\mu \widehat{\phi}\, \partial_\nu \widehat{\phi} - V_{\rm HI}\right),\;\; \text{with} \;\; V_{\rm HI} = \widehat{V}_{\rm HF} + V_{\rm HD}/f^2$$

Where ϕ Stands For $h, \theta_+, \theta_-, \theta_\nu, x_1, x_2, \bar{x}_1, \bar{x}_2$ and S.

The D-Flat Direction of the SUGRA Potential

- If We Use The Parameterization: $\boxed{\nu^c_H = he^{i\theta}\cos\theta_\nu/\sqrt{2} \ \text{ and } \ \bar{\nu}^c_H = he^{i\bar\theta}\sin\theta_\nu/\sqrt{2}}$ Where h is the Inflaton,

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$$\theta=\bar\theta=0,\ \theta_\nu=\pi/4 \ \text{ and } \ e^c_H=\bar e^c_H=u^c_H=\bar u^c_H=d^c_H=\bar d^c_H=g^c=\bar g^c=0.$$

- Along this Direction, $V_{\rm HD}$ Vanishes And so, $V_{\rm HI}=\widehat{V}_{\rm HF}$ takes the form

$$V_{\rm HI0}=m_{\rm P}^4\frac{\lambda^2(x_h^2-4m_{\rm PS}^2)^2}{16f^2} \ \text{ with } \ f=1+c_{\mathcal R}x_h^2,\ \ m_{\rm PS}=\frac{M_{\rm PS}}{m_{\rm P}},\ \ x_h=\frac{h}{m_{\rm P}} \ \text{ and } \ c_{\mathcal R}=-\frac16+\frac{k_H}{4}\cdot$$

- For $c_{\mathcal R}\gg1$, $V_{\rm HI0}$ and the Corresponding Hubble Parameter $\widehat{H}_{\rm HI0}$ Become Almost Constant And Are Given By

$$V_{\rm HI0}=\frac{\lambda^2h^4}{16f^2}\simeq\frac{\lambda^2m_{\rm P}^4}{16c_{\mathcal R}^2} \ \text{ and } \ \widehat{H}_{\rm HI0}=\frac{V_{\rm HI0}^{1/2}}{\sqrt3 m_{\rm P}}\simeq\frac{\lambda m_{\rm P}}{4\sqrt3 c_{\mathcal R}}\cdot$$

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$$\frac{d\widehat{h}}{dh}=J=\sqrt{\frac1f+\frac{6c_{\mathcal R}^2x_h^2}{f^2}},\ \ \widehat{\theta}_+=\frac{Jh\theta_+}{\sqrt2},\ \ \widehat{\theta}_-=\frac{h\theta_-}{\sqrt{2f}},\ \ \widehat{\theta}_\nu=\frac{h\theta_\nu}{\sqrt f} \ \text{ and } \ \widehat{\chi}=\frac{\chi}{\sqrt f}\cdot$$

Where $\chi=S,x_1,x_2,\bar x_1$ and $\bar x_2$ Are The Fluctuations Of The Various Fields. We Expand Them In Real And Imaginary Parts As

Follows $X=(x_1+ix_2)/\sqrt2,\ \ \bar X=(\bar x_1+i\bar x_2)/\sqrt2$ where $X=e^c_H,u^c_H,d^c_H,g^c$ and $x=e,u,d,g.$

Therefore The Action Takes The Form

$$\mathcal{S}_{\rm HI}=\int d^4x\sqrt{-\widehat{g}}\left(-\frac12 m_{\rm P}^2\widehat{\mathcal R}+\frac12\widehat{g}^{\mu\nu}\sum_\phi\partial_\mu\widehat{\phi}\partial_\nu\widehat{\phi}-V_{\rm HI}\right), \ \text{ with } \ V_{\rm HI}=\widehat{V}_{\rm HF}+V_{\rm HD}/f^2$$

Where ϕ Stands For $h,\theta_+,\theta_-,\theta_\nu,x_1,x_2,\bar x_1,\bar x_2$ and S.

Stability of the Inflationary Trajectory

- We Have The Following Pattern of SSB

$$SU(4)_{\rm C} \times SU(2)_{\rm R} \to SU(3)_{\rm C} \times U(1)_Y.$$
$(15 + 3 \to 8 + 1$ Generators)

We Observe the Following:

- All mass$^2 > 0$. Especially
  - ♦ $m^2_{\widehat{S}} > 0 \;\Leftrightarrow\; k_S > 1/6f$,
  - ♦ $m^2_{\widehat{\theta}\nu} > 0$ and $m^2_{\widehat{u}-} > 0$ Since They Include Terms Proportional to $g \simeq 0.7 > \lambda$,
  - ♦ $m^2_{\widehat{d}-} > 0$ for $\lambda_H \simeq 1$.
- The Numbers Of Bosonic And Fermionic d.o.f (Degrees of Freedom) in Each Sector Are Equal.
- All mass$^2 > \widehat{H}^2_{\rm HI}$ and So Any Inflationary Perturbations Of The Fields Other Than The Inflaton Are Safely Eliminated.
- The One-Loop Radiative Corrections Have No Significant Effect On The Inflationary Dynamics And Predictions, Since The Slope Of The Inflationary Path Is Generated At The Classical Level.

The Scalar Mass Spectrum Along The Inflationary Trajectory

Fields	Masses Squared	Eigenstates
The $S - \nu^c_H - \bar\nu^c_H$ Sector		
2 Real	$m^2_{\widehat{\theta}\nu} = m^2_{\rm P} x^2_h \left(2\lambda^2(x^2_h - 6) + 15g^2 f\right)/24f^2$	$\widehat{\theta}_\nu$
Scalars	$m^2_{\widehat{\theta}+} = \lambda^2 m^4_{\rm P} x^2_h \left(1 + 6c_{\mathcal{R}}\right)/12J^2 f^3 \simeq 4\widehat{H}^2_{\rm HI}$	$\widehat{\theta}_+$
1 Complex	$m^2_{\widehat{S}} = \lambda^2 m^2_{\rm P} x^2_h \left(12 + x^2_h \bar f\right)(6k_S f - 1)\,/$	$\widehat{S}$
Scalar	$/6f^2 \bar f$ With $\bar f = f + 6c^2_{\mathcal{R}} x^2_h$	
The $u^c_{H{\rm a}} - \bar u^c_{H{\rm a}}$ (a $= 1,2,3$) and $e^c_H - \bar e^c_H$ Sectors		
$2(3+1)$ Real	$m^2_{\widehat{u}-} = m^2_{\rm P} x^2_h \left(\lambda^2(x^2_h - 3) + 3g^2 f\right)/12f^2$	$\widehat{u}^{\rm a}_{1-}, \widehat{u}^{\rm a}_{2+}$,
Scalars	$m^2_{\widehat{e}-} = m^2_{\widehat{u}-}$	$\widehat{e}_{1-}, \widehat{e}_{2+}$
The $d^c_{H{\rm a}} - \bar d^c_{H{\rm a}}$ and $g^c_{\rm a} - \bar g^c_{\rm a}$ (a $= 1,2,3$) Sectors		
$3 \cdot 8$ real	$m^2_{\widehat{g}} = m^2_{\rm P} x^2_h \left(\lambda^2 x^2_h + 24\lambda^2_{\bar H} f\right)/24f^2$	$\widehat{g}^{\rm a}_1, \widehat{g}^{\rm a}_2$
scalars	$m^2_{\widehat{\bar g}} = m^2_{\rm P} x^2_h \left(\lambda^2 x^2_h + 24\lambda^2_H f\right)/24f^2$	$\widehat{\bar g}^{\rm a}_1, \widehat{\bar g}^{\rm a}_2$
	$m^2_{\widehat{d}+} = m^2_{\rm P} x^2_h \left(\lambda^2 + 4\lambda^2_H f\right)/4f^2$	$\widehat{d}^{\rm a}_{1+}, \widehat{d}^{\rm a}_{2-}$
	$m^2_{\widehat{d}-} = m^2_{\rm P} x^2_h \left(\lambda^2\left(x^2_h - 3\right) + 12\lambda^2_H f\right)/12f^2$	$\widehat{d}^{\rm a}_{1-}, \widehat{d}^{\rm a}_{2+}$

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	$m^2_{\widehat{\theta}+}=\lambda^2m^4_{\rm P}x^2_h\,(1+6c_{\mathcal R})\,/12J^2f^3\simeq 4\widehat{H}^2_{\rm HI}$	$\widehat{\theta}_+$
1 Complex Scalar	$m^2_{\widehat{S}}=\lambda^2m^2_{\rm P}x^2_h\left(12+x^2_h\bar f\right)(6k_Sf-1)\,/$ $/6f^2\bar f$ With $\bar f=f+6c^2_{\mathcal R}x^2_h$	$\widehat{S}$
	The $u^c_{H{\rm a}}-\bar u^c_{H{\rm a}}$ $({\rm a}=1,2,3)$ and $e^c_H-\bar e^c_H$ Sectors	
$2(3+1)$ Real Scalars	$m^2_{\widehat{u}-}=m^2_{\rm P}x^2_h\left(\lambda^2(x^2_h-3)+3g^2f\right)/12f^2$	$\widehat{u}^{\rm a}_{1-},\ \widehat{u}^{\rm a}_{2+},$
	$m^2_{\widehat{e}-}=m^2_{\widehat{u}-}$	$\widehat{e}_{1-},\ \widehat{e}_{2+}$
	The $d^c_{H{\rm a}}-\bar d^c_{H{\rm a}}$ and $g^c_{\rm a}-\bar g^c_{\rm a}$ $({\rm a}=1,2,3)$ Sectors	
$3\cdot 8$ real scalars	$m^2_{\widehat{g}}=m^2_{\rm P}x^2_h\left(\lambda^2x^2_h+24\lambda^2_{\bar H}f\right)/24f^2$	$\widehat{g}^{\rm a}_1,\widehat{g}^{\rm a}_2$
	$m^2_{\widehat{\bar g}}=m^2_{\rm P}x^2_h\left(\lambda^2x^2_h+24\lambda^2_{H}f\right)/24f^2$	$\widehat{\bar g}^{\rm a}_1,\widehat{\bar g}^{\rm a}_2$
	$m^2_{\widehat{d}+}=m^2_{\rm P}x^2_h\left(\lambda^2+4\lambda^2_Hf\right)/4f^2$	$\widehat{d}^{\rm a}_{1+},\widehat{d}^{\rm a}_{2-}$
	$m^2_{\widehat{d}-}=m^2_{\rm P}x^2_h\left(\lambda^2\left(x^2_h-3\right)+12\lambda^2_Hf\right)/12f^2$	$\widehat{d}^{\rm a}_{1-},\widehat{d}^{\rm a}_{2+}$

Approximating the Inflationary Dynamics

- The number of e-foldings, $\widehat{N}_*$, That The Scale k_* Suffers During non-MHI Can Be Calculated Via The Relation

$$\widehat{N}_* \simeq \frac{3c_{\mathcal{R}}}{4}\frac{h_*^2 - h_{\rm f}^2}{(1+4c_{\mathcal{R}}m_{\rm PS}^2)m_{\rm P}^2} \Rightarrow h_* \simeq 2m_{\rm P}\sqrt{\widehat{N}_*\left(1+4c_{\mathcal{R}}m_{\rm PS}^2\right)/3c_{\mathcal{R}}}.$$

where h_* is the value of h when k_* Crosses The Inflationary Horizon. Also $h_{\rm f} \ll h_*$ is the value of h at the end of non-MHI Determined By The Criterion

$$\max\{\widehat{\epsilon}(h_{\rm f}), |\widehat{\eta}(h_{\rm f})|\} = 1, \quad \text{where} \quad \widehat{\epsilon} \simeq \frac{4m_{\rm P}^4\left(1+4c_{\mathcal{R}}m_{\rm PS}^2\right)^2}{3c_{\mathcal{R}}^2h^4} \quad \text{and} \quad \widehat{\eta} \simeq -\frac{4m_{\rm P}^2\left(1+4c_{\mathcal{R}}m_{\rm PS}^2\right)}{3c_{\mathcal{R}}h^2}$$

The Numerical Computation Reveals That non-MHI Terminates Due To The Violation of the $\widehat{\epsilon}$ Criterion at

$$h = h_{\rm f} = (4/3)^{1/4}\, m_{\rm P}\sqrt{\left(1+4c_{\mathcal{R}}m_{\rm PS}^2\right)/c_{\mathcal{R}}}.$$

We Observe that $h_{\rm f}$ Increases as $c_{\mathcal{R}}$ or λ Decreases – see Below.

- The Power Spectrum $P_{\mathcal{R}}$ of the Curvature Perturbations Generated by h at the Pivot Scale k_* is

$$P_{\mathcal{R}}^{1/2} \simeq \frac{\lambda h_*^2}{16\sqrt{2}\pi m_{\rm P}^2\left(1+4c_{\mathcal{R}}m_{\rm PS}^2\right)} \simeq \frac{\lambda\widehat{N}_*}{12\sqrt{2}\pi c_{\mathcal{R}}}.$$

Confronting This Result With The WMAP7 data, we obtain

$$\lambda \simeq 8.4\cdot 10^{-4}\pi c_{\mathcal{R}}/\widehat{N}_* \Rightarrow \underline{c_{\mathcal{R}} \simeq 20925\,\lambda} \quad \text{for} \quad \widehat{N}_* \simeq 55.$$

The Required $c_{\mathcal{R}}$ Turns Out To Be A Little Lower Than The One In non-SUSY Case.

- The Remaining Inflationary Observables turn out to be Identical with the non-SUSY case:

$$n_{\rm s} \simeq 1 - 2/\widehat{N}_*, \quad \alpha_{\rm s} \simeq -2\widehat{\xi}_* \simeq -2/\widehat{N}_*^2 \quad \text{and} \quad r \simeq 12/\widehat{N}_*^2$$

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- At the SUSY Vacuum, The Inflaton And The RH Neutrinos, $\widehat{\nu}^c_i$, Acquire Masses $m_{\rm I}$ and $M_{i\widetilde{\nu}^c}$ Respectively Given by

$$m_{\rm I} \simeq \frac{\sqrt{2}\lambda M_{\rm PS}}{f_0 J_0} \simeq \frac{\lambda m_{\rm P}}{2\sqrt{3}c_{\mathcal R}} \simeq \frac{10^{-4} m_{\rm P}}{4.2\sqrt{3}} \simeq 3\cdot 10^{13}~{\rm GeV} \quad\text{for}\quad \lambda \gtrsim \frac{10^{-4}}{4.2\sqrt{6}m_{\rm PS}} \simeq 1.3\cdot 10^{-3} \quad\text{and}\quad M_{i\widetilde{\nu}^c} = 2\lambda_{i\nu^c}\frac{M^2_{\rm PS}}{M_{\rm S}\sqrt{f_0}}$$

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Which Gives Rise To The Following Decay Width

$$\Gamma_{{\rm I}\nu^c} = \frac{c^2_{{\rm I}\nu^c}}{64\pi}m_{\rm I}\sqrt{1-\frac{4M^2_{{\rm I}\widetilde{\nu}^c}}{m^2_{\rm I}}} \quad\text{with}\quad c_{{\rm I}\nu^c} = \frac{M_{{\rm I}\widetilde{\nu}^c}}{M_{\rm PS}}\frac{f_0^{3/2}}{J_0}\left(1-12c_{\mathcal R}m^2_{\rm PS}\right),$$

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$$\mathcal{L}_{{\rm I}y} = 6yc_{\mathcal R}\frac{M_{\rm PS}}{m^2_{\rm P}}\frac{f_0^{3/2}}{2J_0}\widehat{\delta h}\left(\widetilde{X}\widehat{\psi}_Y\widehat{\psi}_Z + \widetilde{Y}\widehat{\psi}_X\widehat{\psi}_Z + \widetilde{Z}\widehat{\psi}_X\widehat{\psi}_Y\right) + {\rm h.c.},$$

Where y is a Yukawa Coupling Constant and $\mathcal{L}_{{\rm I}y}$ Arises from a Typical Trilinear Superpotential Term Of The Form $W_y = yXYZ$ With ψ_X, ψ_Y and ψ_Z Chiral Fermions Associated With The Superfields X, Y And Z, Whose Scalar Components Are Denoted With The Superfield Symbol. $\mathcal{L}_{{\rm I}y}$ Gives Rise To The Following 3-Body Decay Width

$$\Gamma_{{\rm I}y} = \frac{14c^2_{{\rm I}y}}{512\pi^3}m^3_{\rm I} \simeq \frac{3y^2_{33}}{64\pi^3}f_0^3\left(\frac{m_{\rm I}}{m_{\rm P}}\right)^2 m_{\rm I} \quad\text{where}\quad c_{{\rm I}y} = 6y_{33}c_{\mathcal R}\frac{M_{\rm PS}}{m^2_{\rm P}}\frac{f_0^{3/2}}{J_0} \quad\text{and}\quad y_{33} \simeq (0.4-0.6).$$

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A Scenario of non-Thermal Leptogenesis

- The Reheating Temperature, $T_{\rm rh}$, is Exclusively Determined By The Inflaton Decay And Is Given By

$$T_{\rm rh}=\left(\frac{72}{5\pi^2 g_*}\right)^{1/4}\sqrt{\Gamma_{\rm I} m_{\rm P}}\quad \text{with}\quad \Gamma_{\rm I}=\Gamma_{{\rm I}\nu^c}+\Gamma_{{\rm I}y},\quad \text{and}\quad g_*\simeq 228.75$$

where g_* Counts The Effective Number Of Relativistic Degrees Of Freedom At Temperature $T_{\rm rh}$.

- The Subsequent Out-of-Equilibrium (since $M_{{\rm I}\widehat{\nu}^c}>T_{\rm rh}$) Decay of $\widehat{\nu}^c_{\rm I}$ Gives Rise to A B Yield Which Can Be Computed As

$$Y_B=-0.35\cdot 2\varepsilon_L\,\frac{5}{4}\,\frac{\Gamma_{{\rm I}\nu^c}}{\Gamma_{\rm I}}\,\frac{T_{\rm rh}}{m_{\rm I}}\cdot$$

- In The Major Part Of Our Parameter Space $\Gamma_{\rm I}\simeq\Gamma_{{\rm I}y}$ and so The Branching Ratio Of The Produced $\widehat{\nu}^c_i$ Is Given By

$$\frac{\Gamma_{{\rm I}\nu^c}}{\Gamma_{\rm I}}\simeq\frac{\Gamma_{{\rm I}\nu^c}}{\Gamma_{{\rm I}y}}=\frac{\pi^2\left(1-12c_{\mathcal{R}}m_{\rm PS}^2\right)^2}{72c_{\mathcal{R}}^2 y_{33}^2 m_{\rm PS}^4}\,\frac{M^2_{{\rm I}\widehat{\nu}^c}}{m_{\rm I}^2}\cdot$$

For $M_{{\rm I}\widehat{\nu}^c}\simeq\left(10^{11}-10^{13}\right){\rm GeV}$ the Ratio Above Takes Adequately Large Values So That Y_L is Sizable.

- We Assume That the Inflaton Decays to the Lightest RH Neutrino, $\widehat{\nu}^c_1$ and That The Majorana Masses of $\widehat{\nu}^c_i$ Are Hierarchical, With $M_{1\widehat{\nu}^c}\ll M_{2\widehat{\nu}^c}, M_{3\widehat{\nu}^c}$ (but with $M_{1\widehat{\nu}^c}>T_{\rm rh}$). For a Normal Hierarchical Mass Spectrum Of Light Neutrinos ε_L Reads:

$$\varepsilon_L=-\frac{3}{8\pi}\frac{m_{\nu_\tau}M_{1\widehat{\nu}^c}}{\langle H_u\rangle^2}\delta_{\rm eff},\quad \text{with}\quad |\delta_{\rm eff}|\leq 1\quad \text{And}\quad m_{\nu_\tau}=\sqrt{\Delta m^2_\oplus}=0.05\ {\rm eV}.$$

- The $\widetilde{G}$ Yield At The Onset of BBN Is Estimated To Be:

$$Y_{\widetilde{G}}\simeq c_{\widetilde{G}}T_{\rm rh}\quad \text{with}\quad c_{\widetilde{G}}=1.9\cdot 10^{-22}/{\rm GeV}.$$

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Cosmological Requirements

(i) The Number of e-foldings $N_{\rm HI*}$ That the Scale k_* Suffered During FHI has to be Sufficient to Resolve the Horizon and Flatness Problems of *Standard Big Bang* (SBB) Cosmology:

$$\widehat{N}_* \simeq 22.5 + 2\ln\frac{V_{\rm HI}(h_*)^{1/4}}{1~{\rm GeV}} - \frac{4}{3}\ln\frac{V_{\rm HI}(h_{\rm f})^{1/4}}{1~{\rm GeV}} + \frac{1}{3}\ln\frac{T_{\rm rh}}{1~{\rm GeV}} + \frac{1}{2}\ln\frac{f(h_{\rm f})}{f(h_*)}.$$

(ii) The Inflationary Observables are to be Consistent With the Fitting of the WMAP7 Results by the ΛCDM Model:

$$P_{\mathcal{R}*}^{1/2} \simeq 4.93\cdot10^{-5},\quad n_{\rm s}=0.968\pm0.024,\quad -0.062\leq a_{\rm s}\leq 0.018\ \ \text{and}\ \ r<0.24,\ \ \text{at 95\% c.l.}$$

(iii) We Can Identify The Highest Mass Scale of the Model in the SUSY Vacuum With The Unification Scale $M_{\rm GUT}$, Within the MSSM. i.e.

$$m_{\perp0} = \sqrt{\frac{5}{2}}\frac{gM_{\rm PS}}{f_0} = M_{\rm GUT} \Rightarrow M_{\rm PS} = \frac{\sqrt{2}M_{\rm GUT}m_{\rm P}}{(5g^2m_{\rm P}^2 - 2c_{\mathcal{R}}M_{\rm GUT}^2)^{1/2}} \simeq (1.81-2.2)\cdot10^{16}~{\rm GeV}.$$

(iv) The Validity Of The Effective Theory Below $\Lambda = m_{\rm P}/c_{\mathcal{R}}$ implies $V_{\rm HI}(h_*)^{1/4}\leq\Lambda$ or $\widehat{H}_*\leq\Lambda$ for $c_{\mathcal{R}}\geq1$.

(v) To Ensure That The Inflaton Decay To RH Neutrinos Is Kinematically Allowed We Have To Impose The Constraint:

$$m_{\rm I}\geq 2M_{\rm I\nu^c} \quad\Rightarrow\quad M_{\rm I\nu^c}\lesssim \lambda m_{\rm P}/4\sqrt{3}c_{\mathcal{R}}\simeq 1.5\cdot10^{13}~{\rm GeV}\ \ \text{for}\ \ \lambda\gtrsim1.3\cdot10^{-3}.$$

(vi) The Implementation Of BAU via non-Thermal Leptogenesis Dictates at 95% c.l.

$$Y_B = (8.74\pm0.42)\cdot10^{-11} \Rightarrow 8.32\leq Y_B/10^{-11}\leq 9.16.$$

(vii) Assuming Unstable $\widetilde{G}$, We Impose an Upper Bound[11] on $Y_{\widetilde{G}}$ In Order to Avoid Problems With the SBB Nucleosynthesis:

$$Y_{\widetilde{G}}\lesssim\begin{cases}10^{-13}\\10^{-12}\end{cases}\Rightarrow T_{\rm rh}\lesssim\begin{cases}5.3\cdot10^{8}~{\rm GeV}\\5.3\cdot10^{9}~{\rm GeV}\end{cases}\ \text{for } \widetilde{G}\text{ Mass } m_{\widetilde{G}}\simeq\begin{cases}10.6~{\rm TeV}\\13.5~{\rm TeV.}\end{cases}$$

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[11] *M. Kawasaki, K. Kohri, and T. Moroi (2005); J.R. Ellis, K.A. Olive, and E. Vangioni (2005).*

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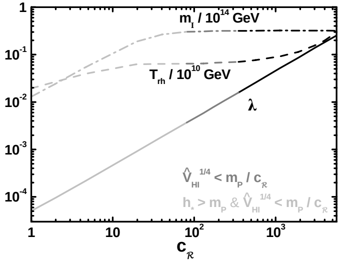

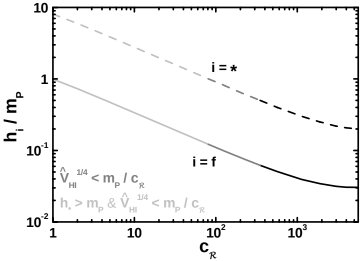

$$1 \lesssim c_{\mathcal{R}} \lesssim 5.6 \cdot 10^3 \quad \text{and} \quad 5 \cdot 10^{-5} \lesssim \lambda \lesssim 0.25 \quad \text{for} \quad 53.9 \lesssim \widehat{N}_* \lesssim 55.$$

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Clearly, the Predicted $\alpha_{\rm s}$ and r Lie Within The Allowed Ranges Whereas $n_{\rm s}$ Turns Out To Be Impressively Close To Its Central Observationally Favored Value.

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We set $\lambda_H = \lambda_{\bar{H}} = 0.5$, $k_S = 1, g = 0.7$ and $y_{33} = 0.5$. Imposing all the Observational Constraints we Obtain the Following Allowed Masses of $\widetilde{\nu}_i^c$ versus λ for the The Considered Scenario of Non-thermal Leptogenesis

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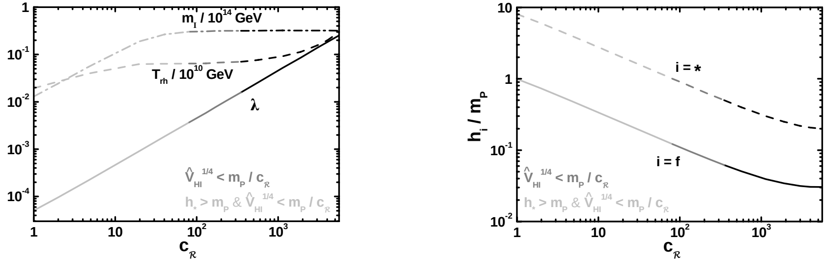

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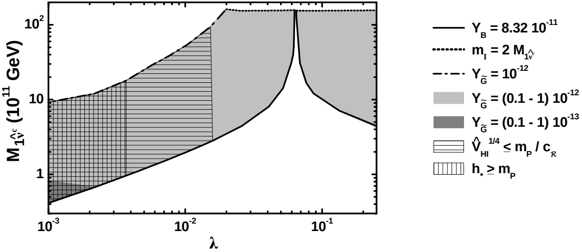

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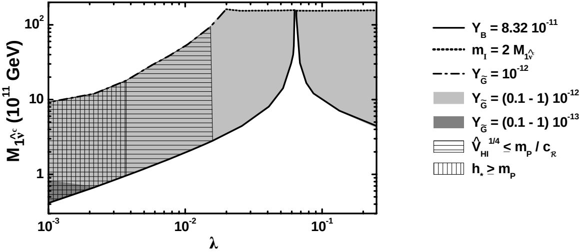

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