Embedding MSSM Inflation into the Minimal Left-Right Symmetric Model

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Work in progress, with M. Drees
The universe dominated by a scalar field ("inflaton"), $\phi$:
\[ \dddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0. \]

Exponential expanding: $R(t) \propto e^{Ht}$.

$\epsilon \equiv \frac{1}{2} M_P^2 \left( \frac{V'}{V} \right)^2 \ll 1$; $\dot{\phi} = -\frac{V'}{3H}$ (Or, $|\eta \equiv M_P^2 \frac{V''}{V}| << 1$)

"Reheating": After inflation, the inflaton oscillates around the global minimum and produces the entropy density.
(Lifted) Flat Directions in Supersymmetric Theories

The superpotential:

\[ W = W_{\text{renorm}} + \sum_{n>3} \frac{\lambda}{M^{n-3}} \phi^n. \]

⇒ Flat directions in MSSM are lifted by soft SUSY-breaking terms and by non-renormalizable terms. [Gherghetta, Kolda, Martin]

⇒ The scalar potential:

\[ V = \frac{1}{2} m^2 \phi^2 + A \cos(n\theta + \theta_A) \frac{\lambda_n}{nM_P^3} \phi^n + \frac{\lambda^2}{M_P^2(n-3)} \phi^{2(n-1)}. \]
Only n=6 (LLe, udd) flat directions can be inflaton candidates. Parametrized by, e.g.,
\[ L_i = \frac{1}{\sqrt{3}} (0 \phi)^T; \quad L_j = \frac{1}{\sqrt{3}} (\phi 0)^T; \quad e_k = \frac{1}{\sqrt{3}} \phi, \]
The scalar potential is:
\[ V = \frac{1}{2} m^2 \phi^2 - \frac{A \lambda_6}{6 M^3} \phi^6 + \frac{\lambda^2}{M^6} \phi^{10}. \]
Tuning \( A^2 = 40 m^2 \), at the saddle point,
\[ \phi_0 = \left( \frac{m \phi M^3}{\sqrt{10} \lambda_6} \right)^{1/4}; \quad V(\phi_0) = \frac{4}{15} m^2 \phi_0^2, \]
With $m_{\phi} \sim 1 \text{ TeV}, \lambda_6 \sim 1$,

\[ \phi_0 \sim 10^{14} \text{ GeV}; \quad H_{\text{inf}} \sim \frac{m_{\phi}\phi_0}{M_P} \sim (1 - 10) \text{ GeV}; \]

\[ n_s \sim 1 - \frac{4}{N_{\text{COBE}}} \approx 0.92; \quad \delta \sim \frac{m_{\phi}M_P}{\phi_0^2}N_{\text{COBE}}^2 \sim 10^{-5}. \]
The Minimal Left-Right (LR) Symmetric Model [Aulakh et. al.]

- $U(1)_{B-L} \times SU(2)_R \rightarrow U(1)_Y$ by $SU(2)_R$ triplet Higgs.

- Heavy right-handed neutrino is naturally included.
  \[ \Rightarrow m_\nu \sim m_D^2 / M_R \]

- Parity is broken spontaneously.

- Subgroup of SO(10).
The chiral superfields \((SU(3) \times U(1)_{B-L} \times SU(2)_L \times SU(2)_R)\):

\[
Q = (3, 1/3, 2, 1), \quad Q_c = (3^*, -1/3, 1, 2), \quad L = (1, -1, 2, 1)
L_c = (1, 1, 1, 2), \quad H = (1, 0, 2, 2^*), \quad \Sigma = (1, 2, 3, 1)
\]

\[
\Sigma = (1, -2, 3, 1), \quad \Sigma_c = (1, -2, 1, 3), \quad \Sigma_c = (1, 2, 1, 3)
\]

The renormalizable superpotential: (i, j: family index)

\[
W_{\text{ren}} = m_{\Sigma}(\Sigma \Sigma + \Sigma_c \Sigma_c) + Y_q H Q_i Q_j + Y_l H L_i L_j + \frac{1}{2} Y_N^i (L_i \Sigma_c L_j + L_i \Sigma L_j).
\]

The symmetry is broken by nonrenormalizable terms:

\[
W_{\text{nr}} \ni \frac{\lambda_{\sigma}}{4M_P} (\Sigma_c \Sigma_c)^2.
\]

The LR symmetry breaking scale:

\[
10^{13} \text{GeV} \lesssim M_R (= \sqrt{\frac{m_{\Sigma} M_P}{\lambda_{\sigma}}}) \lesssim 10^{16} \text{GeV}.
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\]

The symmetry is broken by nonrenormalizable terms:

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The Set-up

- $Q_c Q_c Q_c L_c$ flat direction: Lift by $n=4$ $Q_c Q_c Q_c L_c$.

  Parametrizing the fields such as

  \[ Q_{ci} = e^{i\theta_\phi} (\phi \ 0)^T, \quad Q_{cj} = e^{i\theta_\phi} (0 \ \phi)^T, \quad Q_{ck} = e^{i\theta_\phi} (0 \ \phi)^T, \quad L_{cj} = c_j e^{i\theta_j} (\psi \ 0)^T, \quad L_{ck} = c_k e^{i\theta_k} (\psi \ 0)^T, \ldots \]

  \( j \neq k; c_j^2 + c_k^2 = 1; c_j, c_k \in \mathbb{R} \), flat directions:

  1. $\psi = \phi; \sigma = \sigma = 0; \cos(2\theta_j - 2\theta_k) = 1 - \frac{1}{2c_j^2 2c_k^2}$.  
     ("LR-symmetric" flat direction)

  2. $\psi = 0; \sigma = \sqrt{-\frac{\phi^2}{4} + \frac{1}{4} \sqrt{\frac{64m^2 M_P^2}{\lambda^2 \sigma^2} + \phi^4}}; \sigma = \sqrt{\frac{\phi^2}{4} + \frac{1}{4} \sqrt{\ldots}}$
     ("MSSM-like" flat direction)

  - $W_{nr} = \frac{\lambda_{\sigma}}{4M_P} (\Sigma c \overline{\Sigma c})^2 + \frac{\lambda_{4j}}{3M_P} \Phi^3 L_{cj} + \frac{\lambda_{4k}}{3M_P} \Phi^3 L_{ck}$. 
The Dynamics

(i) "LR-symmetric" direction ($\bar{\sigma} = \sigma = 0$)

- Constraints:
  - Nucleon (non-)decay $\Rightarrow \lambda_4 \lesssim 10^{-8}$.
  - LR Symmetry breaking $\Rightarrow m_\Sigma \sim m_{\text{soft}}$.

- $V = V_\sigma + V_\phi + V_c$, where

  $V_\sigma = \left( m_\Sigma - \frac{\lambda_\sigma^2}{2M_P} \sigma \bar{\sigma} \right)^2 \left( \sigma^2 + \bar{\sigma}^2 \right) + \frac{1}{2} m^2 \left( \sigma^2 + \bar{\sigma}^2 \right) - \mu^2 \left( \sigma \bar{\sigma} + \text{h.c.} \right) - \frac{\lambda_\sigma^2 A_{\alpha}}{4M_P} \left( \sigma \bar{\sigma} \right)^2,$

  $V_\phi = \frac{1}{2} m_\phi^2 \phi^2 - \frac{\lambda_4 A_4}{4M_P} \phi^4 + \frac{\lambda_4^2}{M_P^2} \phi^6.$

$\Rightarrow \phi_0 = \sqrt{\frac{m_\phi M_P}{\lambda_4}}$

$\Rightarrow$ Consistent with observation.
(ii) "MSSM-like" direction ($\bar{\sigma} \neq 0, \sigma \neq 0$)

We "integrate out" the $\tilde{L}_c$ first: $\tilde{L}_c \simeq -\frac{\lambda_4}{3M_P} \bar{\sigma}^3 \phi^3 \left( \sigma^2 + \frac{\lambda_4 \phi^4}{M_P^2} \right)$

- $\phi \ll M_R : V \simeq \phi^2 \left( m^2 - \frac{\lambda^2 A \phi^4}{M_P^2 M_R} + \frac{\lambda^4 \phi^8}{M_P^4 M_R^2} \right)$
  $\Rightarrow V \rightarrow V_{MSSM}$, with $\lambda^2 \frac{M_P}{M_R} \rightarrow \lambda$.
  $\Rightarrow$ Smaller $\phi_0$.

- $\phi \gg M_R$
  - $\bar{\sigma} \gg \frac{\phi^2}{M_P} : V \simeq \phi^2 \left( m^2 - \frac{\lambda^2 A \phi^5}{M_P^2 M_R^2} + \frac{\lambda^4 \phi^{14}}{M_P^4 M_R^8} \right)$
  $\Rightarrow$ Very complicated fine-tuning needed.

- $\bar{\sigma} \ll \frac{\phi^2}{M_P} : V \simeq m^2 \phi^2 - A M_R^2 \phi + \frac{\lambda^2}{M_P^2} \phi^6$
  $\Rightarrow$ No flat potential.

$\Rightarrow$ Works only for $\phi_0 < M_R$. 
(ii') Assumption: \( \exists \) A symmetry suppressing the \( Q_cQ_cQ_cL_c \).
\[ \Rightarrow W_{nr} = \frac{\lambda_0}{4M_P}(\Sigma_c \overline{\Sigma}_c)^2 + \frac{\lambda_7}{6M_P^4} \phi^6 \Sigma_c. \]

- \( \phi \ll \sqrt{\frac{8m_\Sigma M_P}{\lambda}} : V \simeq \phi^2 \left( m^2 - \frac{A\lambda M_R}{M_P^4} \phi^4 + \frac{\lambda^2 M_R^2}{M_P^8} \phi^8 \right) \)
  \[ \Rightarrow V \rightarrow V_{MSSM}, \text{ with } \lambda \frac{M_R}{M_P} \rightarrow \lambda \]

- \( \phi \gg \sqrt{\frac{8m_\Sigma M_P}{\lambda}} : V \simeq \phi^2 \left( m^2 - \frac{A\lambda}{M_P^4} \phi^5 + \frac{\lambda^2}{M_P^8} \phi^{10} \right) \)
  \[ \Rightarrow \phi_0 \simeq \left( \frac{M_P^4 m}{\lambda_7 M_R} \right)^{1/4} \]

\[ \Rightarrow \text{Slightly larger } \phi_0 \text{ (compared to that in MSSM inflation), but works.} \]
Preheating

- Basic picture [Kofman, Linde, Starobinsky]

Assuming $V = \frac{m^2}{2} \phi^2 + \frac{1}{2} g^2 \phi^2 \chi^2$, EOM for quantum fluctuations of the scalar field $\chi$:

$$\ddot{\chi}_k + 3H\dot{\chi}_k + \left( \frac{k^2}{a^2(t)} + g^2 \Phi(t)^2 \sin^2(m\phi t) \right) \chi_k = 0.$$  

($a$: scale factor, $\Phi$: amplitude of oscillations)

$\Rightarrow$ Parametric resonance can happen!

$\Rightarrow$ Particle production: $n_k = \frac{\omega_k}{2} \left( \frac{\left| \dot{\chi}_k \right|^2}{\omega_k^2} + |\chi_k|^2 \right) - \frac{1}{2}$.

- Post-MSSM inflation [Allahverdi, Enqvist, Garcia-Bellido, Jokinen, Mazumdar]

The gauge bosons and gauginos are produced when the inflaton passes through the origin.

$\Rightarrow$ Get "fatten"s when the inflaton oscillates.

$\Rightarrow$ Decays to the matter fields.
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Particle Production

Post-"MLRSM" inflation - "LR symmetric" direction.

$SU(2)_R \times U(1)_{B-L}$ Symmetry breaking

$\Rightarrow \exists \delta_0 \left( \sim \lambda_{\sigma} \frac{M_R^2}{M_P} \right)$ [Aulakh et. al.]

$\Rightarrow$ All $\phi (\sim TeV)$, $\tilde{L}_c \left( \sim 10^{14} GeV \right)$, $\delta_0 \left( \sim TeV \right)$ start to oscillate.

$\Rightarrow \delta_0$ slowly changing, $\tilde{L}_c$ rapidly fixed at the minimum.

$(m = 10^{-16} M_P, \ m_\Sigma = 10^{-14} M_P, \ \lambda_{\sigma} = 10^{-7}, \ H = 10^{-18} M_P)^N$
Summary Prospects

- Both $n = 4$ and $n = 7$ operator in the $Q_c Q_c Q_c L_c$ direction can provide us the slow-roll inflation, either by tuning the nonrenormalizable coupling or the initial conditions.
  - "LR-symmetric" direction: OK, with suppressed nonrenormalizable couplings.
  - "MSSM-like" direction: $\phi_0$ should lie below $M_R$.  

- The post-inflation cosmology is very different along each branch:
  - "LR-symmetric" direction: Neutral $SU(2)_R$ triplet Higgs ($m \sim \mathcal{O}(\text{TeV})$) is produced.
  - "MSSM-like" direction: All vacuum energy is transferred to the radiation.
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Combining the information from cosmological observation with the collider signal, the model can be strongly constrained.

Implications on Baryogenesis will be explored.