Embedding MSSM Inflation into the Minimal Left-Right Symmetric Model

Ju Min Kim

University of Bonn

10, Sep., 2008

Work in progress, with M. Drees

Outline

Slow-roll Inflation

- Basic picture
  - The universe dominated by a scalar field ("inflaton"), ϕ: $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$.
  - Exponential expanding: $R(t) \propto e^{Ht}$.
  - $\epsilon \equiv \frac{1}{2}M_P^2(V'/V)^2 \ll 1$; $\dot{\phi} = -\frac{V'}{3H}$ (Or, $|\eta \equiv M_P^2 V''/V| << 1$)
  - "Reheating": After inflation, the inflaton oscillates around the global minimum and produces the entropy density.
- Examples of Inflationary Models
  - Chaotic inflation : $V(\phi) = \frac{1}{2}m^2\phi^2$.
  - Hybrid inflation : $V(\phi, \psi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}(\psi^2 - M^2)^2 + \frac{1}{2}\lambda'\psi^2\phi^2$.

Flat Directions in Supersymmtric Theories

The scalar potential:

$$V = |F_i|^2 + \frac{1}{2} D^a D^a,$$

where

$$F_i = -\frac{\partial W^\dagger}{\partial \Phi_i^\dagger}|, \quad D^a = -g \phi_i^\dagger T_{ij}^a \phi_j$$

Flat directions: The field configuration such that the renormalizable scalar potential vanishes identically.

(Lifted) Flat Directions in Supersymmetric Theories

The superpotential:

$$W = W_{renorm} + \sum_{n>3} \frac{\lambda}{M^{n-3}} \Phi^n .$$

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

$\Rightarrow$ The scalar potential:

$$V = \frac{1}{2} m_\phi^2 \phi^2 + A\cos(n\theta + \theta_A) \frac{\lambda_n}{n M_P^3} \phi^n + \frac{\lambda_n^2}{M_P^2 (n-3)} \phi^{2(n-1)} .$$

MSSM Inflation [Allahverdi, Enqvist, Mazumdar]

Only n=6 (LLe, udd) flat directions can be inflaton candidates.
Parametrized by, e.g.,
$L_i = \frac{1}{\sqrt{3}}(0 \quad \phi)^T; \quad L_j = \frac{1}{\sqrt{3}}(\phi \quad 0)^T; \quad e_k = \frac{1}{\sqrt{3}}\phi,$
The scalar potential is:

$$V = \frac{1}{2}m_\phi^2\phi^2 - \frac{A\lambda_6}{6M_P^3}\phi^6 + \frac{\lambda_6^2}{M_P^6}\phi^{10}.$$

Tuning $A^2 = 40m_\phi^2$, at the saddle point,

$$\phi_0 = \left(\frac{m_\phi M_P^3}{\sqrt{10}\lambda_6}\right)^{1/4}; \quad V(\phi_0) = \frac{4}{15}m_\phi^2\phi_0^2,$$

With $m_\phi \sim 1TeV, \lambda_6 \sim 1$,

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

$$n_s \simeq 1 - \frac{4}{N_{COBE}} \simeq 0.92; \quad \delta \simeq \frac{m_\phi M_P}{\phi_0^2} N_{COBE}^2 \sim 10^{-5}.$$

MSSM Inflation: Summary

- Gauge-invariant combination of squarks and/or sleptons as inflaton. $\Rightarrow$ No ad-hoc singlet.
- Needs fine-tuning condition: $A^2 = 40m_{\phi}^2$.
- Testible in laboratory experiments with mild assumptions.
- Low-scale inflation: $H_{inf} \sim (1-10)\mathrm{GeV}$

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 ($SU(3) \times U(1)_{B-L} \times SU(2)_L \times SU(2)_R$):

$$\begin{gathered} Q = (3, 1/3, 2, 1), \quad Q_c = (3^*, -1/3, 1, 2), \quad L = (1, -1, 2, 1) \\ L_c = (1, 1, 1, 2), \quad H = (1, 0, 2, 2^*), \quad \overline{\Sigma} = (1, 2, 3, 1) \\ \Sigma = (1, -2, 3, 1), \quad \overline{\Sigma}_c = (1, -2, 1, 3), \quad \Sigma_c = (1, 2, 1, 3) \end{gathered}$$

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

$W_{ren} =$
$m_\Sigma(\Sigma\overline{\Sigma} + \Sigma_c\overline{\Sigma}_c) + Y_q^{ij} H Q_i Q_{cj} + Y_l^{ij} H L_i L_{cj} + \frac{i}{2} Y_N^{ij}(L_{ci}\overline{\Sigma}_c L_{cj} + L_i \overline{\Sigma} L_j).$

The symmetry is broken by nonrenormalizable terms:

$$W_{nr} \ni \frac{\lambda_\sigma}{4M_P}(\Sigma_c\overline{\Sigma}_c)^2.$$

The LR symmetry breaking scale:

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

The chiral superfields ($SU(3)\times U(1)_{B-L}\times SU(2)_L\times SU(2)_R$):

$$Q=(3,1/3,2,1),\quad Q_c=(3^*,-1/3,1,2),\quad L=(1,-1,2,1)$$
$$L_c=(1,1,1,2),\quad H=(1,0,2,2^*),\quad \overline{\Sigma}=(1,2,3,1)$$
$$\Sigma=(1,-2,3,1),\quad \overline{\Sigma}_c=(1,-2,1,3),\quad \Sigma_c=(1,2,1,3)$$

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

$$W_{ren}=m_\Sigma(\Sigma\overline{\Sigma}+\Sigma_c\overline{\Sigma}_c)+Y_q^{ij}HQ_iQ_{cj}+Y_l^{ij}HL_iL_{cj}+\frac{i}{2}Y_N^{ij}(L_{ci}\overline{\Sigma}_cL_{cj}+L_i\overline{\Sigma}L_j).$$

The symmetry is broken by nonrenormalizable terms:

$$W_{nr}\ni\frac{\lambda_\sigma}{4M_P}(\Sigma_c\overline{\Sigma}_c)^2.$$

The LR symmetry breaking scale:

$$10^{13}GeV\lesssim M_R\left(=\sqrt{\frac{m_\Sigma M_P}{\lambda_\sigma}}\right)\lesssim 10^{16}GeV.$$

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 $Q_{ci} = e^{i\theta_\phi}(\phi \quad 0)^T, \quad Q_{cj} = e^{i\theta_\phi}(0 \quad \phi)^T, \quad Q_{ck} = e^{i\theta_\phi}(0 \quad \phi)^T, \quad , L_{cj} = c_j e^{i\theta_j}(\psi \quad 0)^T, \quad L_{ck} = c_k e^{i\theta_k}(\psi \quad 0)^T$, ... ($j \neq k; c_j^2 + c_k^2 = 1; c_j, c_k \in \mathbf{R}$), flat directions:
  - $\psi = \phi; \quad \overline{\sigma} = \sigma = 0; \quad cos(2\theta_j - 2\theta_k) = 1 - \frac{1}{2c_j^2 2c_k^2}$. ("LR-symmetric" flat direction)
  - $\psi = 0; \quad \overline{\sigma} = \sqrt{-\frac{\phi^2}{4} + \frac{1}{4}\sqrt{\frac{64 m_\Sigma^2 M_P^2}{\lambda_\sigma^2} + \phi^4}}; \quad \sigma = \sqrt{\frac{\phi^2}{4} + \frac{1}{4}\sqrt{\ldots}}$. ("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 ($\overline{\sigma} = \sigma = 0$)

- Constraints:
  - Nucleon (non-)decay $\Rightarrow \lambda_4 \lesssim 10^{-8}$.
  - LR Symmetry breaking $\Rightarrow m_\Sigma \sim m_{soft}$.
- $V = V_\sigma + V_\phi + V_c$, where

$$V_\sigma = \left(m_\Sigma - \frac{\lambda_\sigma}{2M_P}\sigma\overline{\sigma}\right)^2(\sigma^2 + \overline{\sigma}^2) + \frac{1}{2}m^2(\sigma^2 + \overline{\sigma}^2)$$
$$-\mu^2(\sigma\overline{\sigma} + h.c.) - \frac{\lambda_\sigma A_\sigma}{4M_P}(\sigma\overline{\sigma})^2,$$
$$V_\phi = \frac{1}{2}m_\phi^2\phi^2 - \frac{\lambda_4 A_4}{4M_P}\phi^4 + \frac{\lambda_4^2}{M_P^2}\phi^6.$$

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

$\Rightarrow$ Consistent with observation.

(ii) "MSSM-like" direction ($\overline{\sigma} \neq 0, \sigma \neq 0$)

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

- $\phi \ll M_R$: $V \simeq \phi^2 \left(m^2 - \frac{\lambda^2 A \phi^4}{M_P^2 M_R} + \frac{\lambda^4 \phi^8}{M_P^4 M_R^2} \right)$
  $\Rightarrow V \rightarrow V_{MSSM}$, with $\lambda^2 \frac{M_P}{M_R} \rightarrow \lambda$.
  $\Rightarrow$ Smaller ϕ_0.
- $\phi \gg M_R$
  - $\overline{\sigma} \gg \frac{\phi^2}{M_P}$: $V \simeq \phi^2 \left(m^2 - \frac{\lambda^2 A \phi^5}{M_P^2 M_R^2} + \frac{\lambda^4 \phi^{14}}{M_P^4 M_R^8} \right)$
    $\Rightarrow$ Very complicated fine-tuning needed.
  - $\overline{\sigma} \ll \frac{\phi^2}{M_P}$: $V \simeq m^2 \phi^2 - A M_R^2 \phi + \frac{\lambda^2}{M_P^2} \phi^6$
    $\Rightarrow$ No flat potential.

$\Longrightarrow$ Works only for $\phi_0 < M_R$.

(ii') Assumption: $\exists$ A symmetry suppressing the $Q_c Q_c Q_c L_c$.
$\Rightarrow W_{nr} = \frac{\lambda_\sigma}{4M_P}(\Sigma_c \overline{\Sigma}_c)^2 + \frac{\lambda_7}{6M_P^4}\Phi^6 \Sigma_c$.

- $\phi \ll \sqrt{\frac{8m_\Sigma M_P}{\lambda}} : V \simeq \phi^2 \left(m^2 - \frac{A\lambda M_R}{M_P^4}\phi^4 + \frac{\lambda^2 M_R^2}{M_P^8}\phi^8 \right)$
  $\Rightarrow V \to V_{MSSM}$, with $\lambda \frac{M_R}{M_P} \to \lambda$
- $\phi \gg \sqrt{\frac{8m_\Sigma M_P}{\lambda}} : V \simeq \phi^2 \left(m^2 - \frac{A\lambda}{M_P^4}\phi^5 + \frac{\lambda^2}{M_P^8}\phi^{10} \right)$
  $\Rightarrow \phi_0 \simeq \left(\frac{M_P^4 m}{\lambda_7 M_R} \right)^{1/4}$

$\Rightarrow$ Slightly larger ϕ_0 (compared to that in MSSM inflation), but works.

Preheating

- Basic picture [Kofman, Linde, Starobinsky]

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

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

  (a: scale factor, Φ: amplitude of oscillations)

  $\Rightarrow$ Parametric resonance can happen!

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

- 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.

Preheating

- Basic picture [Kofman, Linde, Starobinsky]

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

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

  (a: scale factor, Φ: amplitude of oscillations)

  $\Rightarrow$ Parametric resonance can happen!

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

- 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.

Particle Production

- Post-"MLRSM" inflation - "LR symmetric" direction.
  $SU(2)_R \times U(1)_{B-L}$ Symmetry breaking
  $\Rightarrow \exists \delta_0$ $(\sim \lambda_\sigma \frac{M_R^2}{M_P})$ [Aulakh et. al.]
  $\Rightarrow$ All ϕ $(\sim TeV)$, $\tilde{L_c}$ $(\sim 10^{14} GeV)$, δ_0 $(\sim TeV)$ start to oscillate.
  $\Rightarrow$ δ_0 slowly changing, $\tilde{L_c}$ rapidly fixed at the minimum.

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: ϕ_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 ($m \sim \mathcal{O}(\mathrm{TeV})$) is produced.
  - "MSSM-like" direction: All vacuum energy is transferred to the radiation.

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: ϕ_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.

- Combining the information from cosmological observation with the collider signal, the model can be strongly constrained.
- Implications on Baryogenesis will be explored.