Non-Singlet Inflaton

Ahmad Moursy

Center for Fundamental Physics
Zewail City of science and Technology

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Outline

1. Single field inflation in supergravity
2. Inflation with a $U(1)$ charged field in supergravity
3. Sneutrino Inflation in supergravity with flipped GUT symmetry
4. SUSY Breaking

Problems in supergravity inflation

- Slow-roll conditions: the eta problem
  shift symmetry - No-scale models
- Minkowski vacuum: fine-tuned value of the cosmological constant. In particular, SUSY breaking in flat space at the end of inflation.
  $W = 0$ at the vacuum for SUSY case - No-scale models
- Single-field inflation, the simplest option and a sufficient condition to avoid unacceptably large isocurvature fluctuations.
  Guarantee that all other fields are stabilized during the inflation
- Connection with low energy physics (TeV SUSY breaking scale)
  Study the reheating scenarios, leptogensis,.....

η-problem in supergravity models of inflation

- The inflaton F-term scalar potential in supergravity

$$V_{inf} = e^{K/m_{Pl}^2}\left(D_\varphi W\, K^{\varphi\bar{\varphi}}\, \overline{D_\varphi W} - \frac{3|W|^2}{m_{Pl}^2}\right), \quad D_\varphi W = W_\varphi + K_\varphi W/m_P^2$$

Expand the Kähler potential around $\varphi = 0$

$$K(\varphi, \bar{\varphi}) = K_0 + K_{\varphi\bar{\varphi}}|_0\, \varphi\bar{\varphi} + \dots.$$

In this case the inflation potential can be expanded as

$$V_{inf} = V_0\left(1 + \frac{\hat{\varphi}\hat{\bar{\varphi}}}{m_{Pl}^2}\right) + \dots..$$

- The inflaton mass is of order Hubble parameter, namely

$$m_{\hat{\varphi}}^2 \sim \frac{V_0}{m_{Pl}^2} \sim 3H^2$$

Accordingly, $\eta = \frac{m_{\hat{\varphi}}^2}{3H^2} \approx 1$ slow-roll corrupted

Shift Symmetry

- Imposing a shift symmetry on the inflaton field, provides a natural solution to the η–problem

$$\phi \;\rightarrow\; \phi + iC$$

- The Kähler potential is independent on the inflaton $\varphi = \sqrt{2}\text{Im}(\phi)$, and has the form

$$K \;\equiv\; K(\phi + \bar{\phi})$$

Single field inflation

- A stabilizer superfield S is added such that potential is bounded from below where the superpotential has the form [Kallosh & Linde]

$$W = S\,f(\phi)$$

- The field S should stabilise to its minimum quickly, then it should have mass larger than the Hubble parameter H. Hence adding a quartic term in S to the Kähler potential will do the job.

$$K = \frac{(\phi + \bar{\phi})^2}{2} + S\bar{S} - \zeta(S\bar{S})^2$$

Inflation with a $U(1)$ charged field in supergravity [1]

- A couple of chiral superfields have opposite $U(1)$ charges and transforms under shift symmetry as follows

$$\begin{aligned}\phi_1 &\rightarrow \phi_1 + ic \\ \phi_2 &\rightarrow \phi_2 + ic\end{aligned}$$

- Gauge invariant Kähler potential and superpotential

$$K = |\phi_1 + \bar{\phi}_2|^2 + |S|^2 - \zeta|S|^4$$

$$W = \lambda S(\phi_1\phi_2 + M^2)$$

[1] L. Heurtier, S. Khalil, A. Moursy, JCAP 1510 (2015) no.10, 045

The Model

- SUSY minimum for the potential $V = V_F + V_D$ is located at

$$\langle S \rangle = 0\,, \quad \langle \phi_1 \phi_2 \rangle = -M^2 \quad \text{and} \quad |\phi_1|^2 = |\phi_2|^2 = M^2 \;(\Rightarrow V_D = 0)$$

- Field redefinitions

$$\begin{aligned} S &\equiv s + i\sigma \\ \phi_1 + \bar{\phi}_2 &\equiv \alpha + i\beta \\ \phi_1 - \bar{\phi}_2 &\equiv \rho\ e^{i\theta/2M} \end{aligned}$$

and the minimum is then given by

$$\langle s \rangle = \langle \sigma \rangle = \langle \alpha \rangle = \langle \beta \rangle = 0 \quad \text{and} \quad \langle \rho \rangle = 2M$$

The model

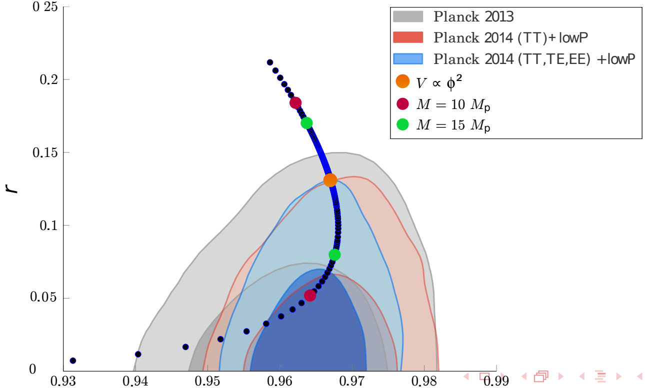
- The field θ is the Nambu Goldstone boson arising after spontaneous breaking of the $U(1)$ gauge symmetry.
- All other fields are spectator fields and are indeed ensured to be heavier than the Hubble scale if $\zeta \gtrsim 1/24$
- V_D vanishes along the inflationary trajectory

$$
\begin{aligned}
(m_s^{\text{inf}})^2 &= (m_\sigma^{\text{inf}})^2 = \lambda^2\rho^2 + 24\,\zeta H^2\,, \\
(m_\alpha^{\text{inf}})^2 &= g^2\rho^2 + 6H^2 - \frac{\lambda^2}{4}(\rho - 4M^2)\,, \\
(m_\beta^{\text{inf}})^2 &= 12\,H^2 + \frac{\lambda^2}{4}\left(4M^2 + \rho^2\right)\,. \\
(m_\rho^{\text{inf}})^2 &= \frac{\lambda^2}{4}(3\rho^2 - 4M^2)
\end{aligned}
$$

Inflationary Observables

- The effective inflationary potential is given by

$$V_{\text{inf}}(\rho) = \frac{\lambda^2}{16}\left(4M^2 - \rho^2\right)^2 \quad (\textit{New Chaotic Inflation})$$



Adding Fayet Illiopoulos terms

- D-term potential

$$V_D = \frac{g^2}{2}\left(|\phi_1|^2 - |\phi_2|^2 + \xi\right)^2$$

- SUSY minimum is modified by FI term

$$|\phi_{1,2}|^2 = \frac{\mp\xi + \sqrt{\xi^2 + 4M^4}}{2}$$

- Defining the basis $\phi_1 \pm \bar{\phi}_2 \equiv \alpha_\pm + i\beta_\pm$ $\Rightarrow$ SUSY vacuum reads

$$\begin{aligned}
\langle s \rangle &= \langle \sigma \rangle = \langle \beta_+ \rangle = \langle \beta_- \rangle = 0\,, \\
\langle \alpha_- \rangle &= \left(2M^2 + \sqrt{\xi^2 + 4M^4}\right)^{1/2}\,, \\
\langle \alpha_+ \rangle &= -\frac{\xi}{\left(2M^2 + \sqrt{\xi^2 + 4M^4}\right)^{1/2}}
\end{aligned}$$

Adding Fayet Illiopoulos terms

- Masses at the SUSY minimum get corrections of order ξ^2/M^2
- FI term back-reacts on the inflationary trajectory and the inflationary potential

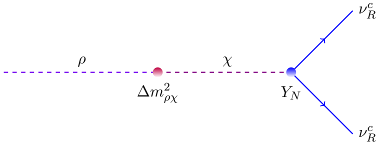
$$V_{inf}(\alpha_-) = \frac{1}{16}\left(8g^2(\xi - \alpha_- A)^2 + \lambda^2 e^{A^2}\left((A^2 - \alpha_-{}^2) + 4M^2\right)^2\right),$$
$$A(\alpha_-) \equiv \frac{8g^2\xi\alpha_-}{\alpha_-{}^2(8g^2 + \lambda^2(\alpha_-{}^2 - 2)) + 16\lambda^2 M^4 - 8\lambda^2 M^2(\alpha_-{}^2 - 1)}$$

- Numerical simulation of the observables in the case $\xi \lesssim M_p \ll M$ provide results identical to the case without FI terms.
- Cases where $\xi \gg 2M$ lead to observables

$$n_s \sim 0.965 \quad \text{and} \quad r \gtrsim 0.2, \qquad (\textit{Excluded by Planck and BICEP II})$$

Reheating

- We consider the kinetic mixing between the inflationary $U(1)$ and $U(1)_{B-L}$.



- The $\rho - \chi$ mixing is given by (χ is the $B-L$ Higgs)

$$\delta_{\rho\chi} = \frac{\tilde{g}\, g_{BL}\, v_{B-L}\, \langle\rho\rangle}{2(m_\rho^2 - m_\chi^2)}$$

- The effective coupling between the inflaton and right-handed neutrinos ($m_\rho \sim v_{B-L} \sim 10^{13}$ GeV)

$$Y_{eff} \simeq \tilde{g}\, g_{B-L} \left(\frac{v_{B-L}}{m_\chi}\right)\left(\frac{M}{m_\chi}\right) Y_N$$

Reheating

- For $m_\chi \sim \mathcal{O}(10^{16})$ GeV, one thus finds $Y_{eff} \simeq \tilde{g}\, g_{B-L}\, Y_N$
- The reheating temperature T_R

$$T_R \approx \frac{(8\pi)^{1/4}}{7} (\Gamma\, M_p)^{1/2} \approx \frac{(8\pi)^{1/4} (M_p\ m_\rho)^{1/2}}{28\sqrt{\pi}} Y_{eff}$$

- Thus $T_R \sim 10^{14}\, \tilde{g}\, g_{B-L}\, Y_N$ GeV. And, for $g_{B-L} \sim \mathcal{O}(0.1)$, $Y_N \sim 10^{-2}$ and $\tilde{g} \sim 10^{-2}$ one gets $T_R \sim 10^9$ GeV

GUT Inflation

- The measured value for the amplitude of scalar perturbations in the CMB

$$A_s = (2.19 \pm 0.11) \times 10^{-9}$$

$$\Rightarrow V = (2 \times 10^{16}\,\mathrm{GeV})^4 \left(\frac{r}{0.15}\right),$$

- Therefore, for a value of $r \sim 0.1$, we have a GUT scale inflation.
- Many of the inflationary SUSY GUTs, suffer from the problem of the GUT monopole problem.
- This topological defect can be avoided if the GUT symmetry is broken during the inflationary era.

Flipped GUT Scenario

- As pointed out by 't Hooft, monopoles do not arise in systems with non-semisimple symmetry groups, i.e. Lie-groups of the form $\mathcal{G} \times U(1)_X$.
- Therefore, flipped GUT scenarios, $SU(5) \times U(1)$ and $SO(10) \times U(1)$, are good candidates.

$$
\begin{aligned}
Y &= \tfrac{1}{5}\left(Q_X - Q_{Y'}\right), & SU(5) \times U(1)_X, \\
Y &= \tfrac{1}{20}\left(5Q_X - Q_Z - 4Q_{Y'}\right), & SO(10) \times U(1)_X,
\end{aligned}
$$

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Flipped GUT Scenario

I will concentrate on $SU(5) \times U(1)_X$ which has more advantages than $SU(5)$:

- Provides a natural solution to the doublet-triplet splitting problem.
- Can easily be extended, via the addition of sterile neutrinos, to accommodate neutrino masses.

Field Content

- The SM particles: $\mathbf{10}_F$, $\bar{\mathbf{5}}_F$ and $\mathbf{1}_F$.
- Electroweak Higgs bosons: $\mathbf{5}_{H_u}$ and $\bar{\mathbf{5}}_{H_d}$.
- The heavy scalars Σ and $\bar{\Sigma}$, triggering the breaking of the flipped $SU(5)$ to the standard model gauge group are contained in representations $\mathbf{10}_H$ and $\overline{\mathbf{10}}_H$.
- An additional superfield, in the conjugate representation of the 10-dimensional matter multiplet $\overline{\mathbf{10}}_F$, is added to allow the introduction of a shift symmetry in the Kähler potential.

	$\mathbf{5}_{H_u}$	$\bar{\mathbf{5}}_{H_d}$	$\bar{\mathbf{5}}_F$	$\mathbf{10}_H$	$\overline{\mathbf{10}}_H$	$\mathbf{10}_F$	$\overline{\mathbf{10}}_F$	$\mathbf{1}_F$	$\mathbf{1}_S$
$U(1)_X$	+2	-2	-3	1	-1	1	-1	5	0
Z_2	+	+	-	+	+	-	-	-	+

Inflationary model [2]

- The gauge invariant superpotential and Kähler potential

$$W \supset S(\lambda_\phi\ \phi_1\phi_2 + \lambda_h\ h_1 h_2 - M^2) + \mu_\phi \phi_1\phi_2$$

$$K = |\phi_1 + \bar{\phi}_2|^2 + |h_1|^2 + |h_2|^2 + |S|^2 - \eta |S|^4$$

- Here, $\phi_{1(2)} \equiv \overset{(-)}{N^c}$, $h_{1(2)}$ as the SM singlet components of $\mathbf{10}$ ($\overline{\mathbf{10}}$) and $S \equiv \mathbf{1}_S$ is a gauge singlet.
- SUSY vacuum

$$\phi_1 = \phi_2 = S = 0 \quad \text{and} \quad h_1 h_2 = \frac{M^2}{\lambda_h} \sim M_{GUT}^2$$

[2] T. E. Gonzalo, L. Heurtier and A. Moursy, JHEP **1706**, 109 (2017)

Inflationary model

- Field redefinitions:

$$\phi_1 + \bar{\phi}_2 = \alpha_1 + i\beta_1\,, \qquad \phi_1 - \bar{\phi}_2 = \alpha_2 + i\beta_2$$

$$S = \frac{s + i\sigma}{\sqrt{2}}\,, \qquad h_{1,2} = \frac{H \pm h}{\sqrt{2}}$$

$$h = \frac{h_r + ih_i}{\sqrt{2}}\,, \qquad H = \rho \exp\left(\frac{i}{\sqrt{2}}\frac{\theta}{M_{GUT}}\right)$$

- At the SUSY vacuum the masses of the real components

$$\begin{aligned} m_s^2 &= m_\sigma^2 \approx M^2\lambda_h\,, \\ m_{\alpha_1}^2 &= m_{\beta_1}^2 = m_{\alpha_2}^2 = m_{\beta_2}^2 \approx \mu_\phi^2\,, \\ m_{h_r} &\approx 2M^2\lambda_h\,, \quad m_{h_i}^2 = \frac{4g^2M^2}{\lambda_h}\,, \quad \text{and} \quad m_\rho^2 \approx 4M^2\lambda_h\,. \end{aligned}$$

Inflationary trajectory

- spectator fields stabilize during inflation and don't perturb inflation

$$\langle \sigma \rangle \;=\; \langle \alpha_1 \rangle = \langle \beta_1 \rangle = \langle h_r \rangle = \langle h_i \rangle = 0$$

and

$$\langle s \rangle = \frac{\sqrt{2}\;\lambda_\phi\;\mu_\phi}{2\eta\lambda_\phi^2 - \mu_\phi^2} \;+\; \ldots$$

where they acquire masses during inflation of order Hubble scale:

$$m_s^2 \;\approx\; m_\sigma^2 \approx 12\eta H^2\,, \quad m_\rho^2 \approx 6H^2$$

$$m_{\alpha_1}^2 \;\approx\; m_{\beta_1}^2 \approx 6H^2\,, \quad m_{h_r}^2 \approx m_{h_i}^2 \approx 3H^2$$

- Shift symmetry $\Rightarrow \phi_1 - \overline{\phi_2} \equiv \alpha_2 + i\beta_2$ slow rolling fields.

Inflationary scenario and Waterfall

- The effective potential during the inflation is given by

$$V(\alpha_2, \beta_2) = \frac{1}{16}\left(\alpha_2^2 + \beta_2^2\right)\left[\left(\alpha_2^2 + \beta_2^2\right)\left(\lambda_\phi^2 - 3\mu_\phi^2\right) + 8(\mu_\phi^2 + \lambda_\phi M^2)\right]$$

$$\Rightarrow V(\Phi) = \frac{1}{16}\Phi^2\left[\Phi^2\left(\lambda_\phi^2 - 3\mu_\phi^2\right) + 8(\mu_\phi^2 + \lambda_\phi M^2)\right] \quad ,$$

with $\Phi^2 = \alpha_2^2 + \beta_2^2$

- Contains quartic and quadratic terms.
- Coefficient of the quartic term should be suppressed.

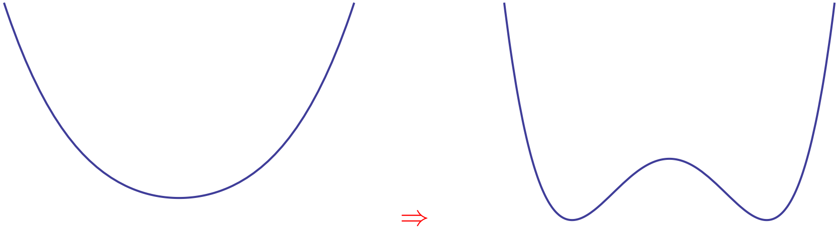
Inflationary scenario and Waterfall

- Field dependent mass of the waterfall field ρ

$$m_\rho^2 \approx \frac{\lambda_\phi^2}{8}\Phi^4 - \frac{\lambda_\phi \lambda_h}{2}\Phi^2$$

$$\Rightarrow \Phi_c^2 \approx \frac{4\lambda_h}{\lambda_\phi}$$

m_ρ^2 becomes negative and we restore the Mexican hat potential for ρ

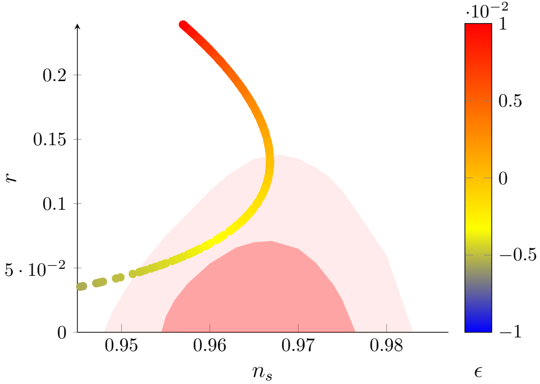


Observables

- Quartic contributions: steepness of the potential

$$\lambda_\phi^2 = (1+\epsilon)3\mu_\phi^2\,, \qquad |\epsilon| \ll 1\,.$$

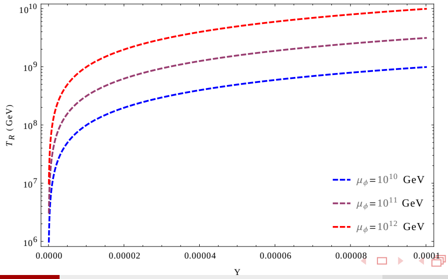
$M_{GUT} = 10^{-2} M_p$ and fix $\phi_c = \phi_{end} = 1 M_p$



- Natural decay channels of the inflaton to the MSSM particles

$$W_{SU(5)} = Y_u\,\bar{\mathbf{5}}_{H_u\alpha}\,\mathbf{10}_F^{\alpha\beta}\,\bar{\mathbf{5}}_{F\beta} + Y_{d1}\,\epsilon_{\alpha\beta\gamma\delta\lambda}\,\mathbf{10}_F^{\alpha\beta}\,\mathbf{10}_F^{\gamma\delta}\,\mathbf{5}_{H_d}^{\lambda} + Y_{d2}\,\epsilon^{\alpha\beta\gamma\delta\lambda}\,\overline{\mathbf{10}}_{F\alpha\beta}\,\overline{\mathbf{10}}_{F\gamma\delta}\,\bar{\mathbf{5}}_{H_u\lambda} + Y_e\,\mathbf{5}_{H_d}^{\lambda}\,\bar{\mathbf{5}}_{F\lambda}\,\mathbf{1}_F$$

$$\Rightarrow \quad \mathcal{L}_{int} = -Y_u\,\tilde{N}^c\left(\nu_L\,\tilde{H}_u^0 + e_L\,\tilde{H}_u^+\right)$$



SUSY breaking effects

- Adding, Polonyi sector

$$\begin{aligned} W_{\not{SUSY}} &= fX + W_0 \\ K_{\not{SUSY}} &= |X|^2 - \xi |X|^4 \end{aligned}$$

f: SUSY breaking scale , $m_{3/2} = W_0$, where for the FGUT scenario

$$W_0 \approx \frac{f}{\sqrt{3 - \frac{2M^2}{\lambda_h}}}$$

- Back-reacts on the inflationary potential

$$V(\Phi) = \frac{1}{16}\Phi^2\left[\Phi^2\left(\lambda_\phi^2 - 3\mu_\phi^2\right) + 8(\mu_\phi(\mu_\phi + 3W_0) + \lambda_\phi M^2)\right].$$

SUSY breaking effects

- In the same approximation regime $\lambda_\phi^2 \approx 3\mu_\phi^2$, in which the quartic term is subdominant, this potential can be written as

$$V(\Phi) \approx \frac{1}{2}\tilde{m}^2\Phi^2$$

where $\tilde{m}^2 = \mu_\phi(\mu_\phi + 3W_0)$.

- $\tilde{m}$ should be of order $10^{-5}M_p$ and upper bound on the SUSY breaking scale

$$f \ll \mu_\phi$$

Conclusions

- A simple model with a charged inflaton under $U(1)$ gauge group and shift symmetry, results in a potential of new chaotic inflation.
- Gauge kinetic mixing between inflationary $U(1)$ and $U(1)_{B-L}$ is proposed, to allow decay channels to right handed neutrinos and reheat the universe.
- Sneutrino inflation can be realized in supergravity framework with flipped $SU(5)$ symmetry.
- Cosmological observables can be accommodated to lay in the $2-\sigma$ region of the Planck measurements.
- To have reheating temperature of order 10^9 GeV, we need $Y_u \sim 10^{-5} \;\Rightarrow\;$ inflaton corresponding to sneutrino from first generation.

Thank you