No Scale SUGRA Inflation

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Based on (PLB 751 (2015)[arXiv:1504.07725], [arXiv:1711.01979].[1]

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Outline

- Introduction
- No scale SUGRA inflation and SO(10) MSGUT
- No scale SUGRA inflation and Type-I seesaw
- Reheating
- SUSY breaking
- Summary

Introduction

- Inflation can solve the problems of standard big bang: Horizon Problem, Flatness problem, Monopole problem and explains observed inhomogeneities over homogeneous background of universe.
- Origin: quantum fluctuations during the inflationary period and are mainly of two type:
  - Scalar: seed of large scale structure $\Longrightarrow$ temperature variation in CMBR measured by WMAP, COBE, PLANCK etc. satellites.
  - Tensor: primordial gravitational waves $\Longrightarrow$ B-mode polarization in CMBR.

cosmological observables

- Scale invariant power spectrum of curvature (density, scalar) perturbations : $P_R = (1.610 \pm 0.01) \times 10^{-9}$, spectral index $n_s = .968 \pm 0.006$ and scale invariance $kdn_s/dk \simeq 0$ (PLANCK, 2016).
- Tensor perturbation(gravity waves) suppressed $P_T/P_R = r < 0.07$.
- $N_{e-folds} \sim$ 50-60.

Plethora of inflationary models

- Within SM the only candidate is SM Higgs, But the negative potential.
- Beyond Standard Model: Link to new physics?
  - Extended scalar sector.
  - The SUSY partner of right handed neutrino.
  - Some axion field.
- String motivated framework of inflation Models
- Focus on: No scale SUGRA motivated Starobinsky inflation models.

No scale SUGRA[3]

- Supersymmetry + gravity = Supergravity (SUGRA).
- No-scale SUGRA:
  - Low energy limit of string theory after compactification[2].
  - The scale of SUSY breaking is not determined to first approximation.
  - Vanishing cosmological constant (at classical level).
- Very first of inflationary model: J. Ellis, Enqvist, Nanopoulos, Olive and Srednicki, 1984.

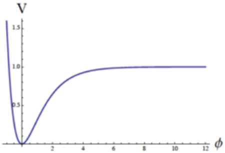
[2] Witten, 1984

[3] Cremmer, Ferrara, Kounnas and Nanopoulos, 1983

Starobinsky Inflation Model (A.A. Starobinsky, PLB 91 (1980))

- Survivor of all cosmological constraints.

$$L = \sqrt{-g}\left(\frac{1}{2}R + \frac{R^2}{12M^2}\right) \equiv$$
$$L = \sqrt{-g}\left(\frac{1}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{3}{4}M^2(1 - e^{-\sqrt{2/3}\phi})^2\right)$$



- It predicts $n_s - 1 = -2/N$ and $r = 12/N^2$. i.e. $n_s \sim .964$, $r \sim .004$ for N=55.

Starobinsky inflation From No-Scale SUGRA[4]

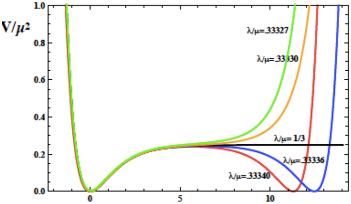
$$K = -3ln(T + T^* - \frac{1}{3}|\phi^2|); \;\; W = \frac{\mu^2}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$$

Fixing $T = T^* = c/2$ gives

$$L_{eff} = \frac{c}{(c - |\phi|^2/3)^2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{(c - |\phi|^2/3)^2}|\frac{\partial W}{\partial\phi}|^2$$

$\phi = \sqrt{3c}\,tanh\frac{\chi}{\sqrt{3}}$ and for $\mu = \lambda/3$

$\Rightarrow V = \mu^2/4(1 - e^{-\sqrt{2/3}\phi})^2$



[4] Ellis et. al. PRL,2013

More than 100 of papers till date

- No scale SUGRA inflation models within GUT
  - SO(10) GUT: Ellis, Garcia, Nanopoulos, Olive (2014), Ellis, Garcia, Nagata, Nanopoulos, Olive(2016), Ellis, H.-J. He, Z.-Z. Xianyu (2016).
  - SU(5): J. Ellis, H.-J. He, Z.-Z. Xianyu (2015), Ellis, Evans, Nagata, Nanopoulos, Olive (2017).
  - Flipped SU(5): J. Ellis, Garcia, Nagata, Nanopoulos, Olive (2017).
- See review article "No scale inflation" by Ellis, Garcia, Nanopoulos, Olive and references therein (more than 100 papers).
- This talk:
  - No scale SUGRA inflation and SO(10) MSGUT
  - No scale SUGRA inflation and Type-I seesaw

SO(10) MSGUT

- The minimal supersymmetric grand unified theory [5] based on SO(10) gauge group Contains: $\mathbf{10}(H_i)$, $\mathbf{210}(\Phi_{ijkl})$ and $\mathbf{126}(\Sigma_{ijklm})(\overline{\mathbf{126}}(\overline{\Sigma}_{ijklm}))$ as Higgs supermultiplets.
- The renormalizable superpotential:

$$W = \frac{m_\Phi}{4!}\Phi^2 + \frac{\lambda}{4!}\Phi^3 + \frac{m_\Sigma}{5!}\Sigma\overline{\Sigma} + \frac{\eta}{4!}\Phi\Sigma\overline{\Sigma} + m_H H^2 + \frac{1}{4!}\Phi H(\gamma\Sigma + \bar{\gamma}\overline{\Sigma})$$

- The **10** and $\overline{\mathbf{126}}$ are required to give masses to the fermions while $\mathbf{126}(\overline{\mathbf{126}})$ breaks the SO(10) gauge symmetry to MSSM together with **210**-plet.
- Different intermediate symmetries are possible with **210**-plet.

[5] Aulakh, Mohapatra(1982), Clark, Kuo and Nakagawa (1983)

- $$\begin{aligned} p &= \langle\Phi(1,1,1)\rangle,\ a = \langle\Phi(15,1,1)\rangle, \\ \omega &= \langle\Phi(15,1,3)\rangle,\ \sigma = \langle\Sigma(\overline{10},3,1)\rangle, \\ \bar{\sigma} &= \langle\bar{\Sigma}(10,3,1)\rangle \end{aligned}$$

- The Superpotential in terms of these *vevs* is,

$$\begin{aligned} W &= m(p^2 + 3a^2 + 6\omega^2) + 2\lambda(a^3 + 3p\omega^2 + 6a\omega^2) \\ &\quad + m_\Sigma \sigma\bar{\sigma} + \eta\sigma\bar{\sigma}(p + 3a - 6\omega) \end{aligned}$$

- $$SO(10) \xrightarrow{210} \text{Intermediate symmetry} \xrightarrow{126} MSSM$$

  For the first step symmetry breaking one can set $|\sigma| = |\bar{\sigma}|$=0.

The intermediate Symmetries

- If $a \neq 0$ and p=ω=0, it gives $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ symmetry.
- If $p \neq 0$ and a=ω=0, this results in $SU(4)_C \times SU(2)_L \times SU(2)_R$ symmetry.
- If $\omega \neq 0$ and p=a=0, it gives $SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$ symmetry.
- If p=a=-$\omega \neq 0$, this has $SU(5) \times U(1)$ symmetry.
- If p=a=$\omega \neq 0$, $SU(5) \times U(1)$ symmetry but with flipped assignments for particles.

No-Scale SUGRA SO(10)[6]

The superpotential in terms of *vevs* of **210** is given as,

$$W = m(p^2 + 3a^2 + 6\omega^2) + 2\lambda(a^3 + 3p\omega^2 + 6a\omega^2)$$

Here $m = m_\Phi$. Similarly no-scale Kähler potential is,

$$K = -3\ln(T + T^* - \frac{1}{3}(|p|^2 + 3|a|^2 + 6|\omega|^2))$$

The F-term potential has the following form,

$$V = e^G \left[\frac{\partial G}{\partial \phi^i} K^i_{j^*} \frac{\partial G}{\partial \phi_{j^*}} - 3 \right]$$

Where $G = K + \ln W + \ln W^*$

- $$V = \frac{1}{\Gamma^2} \left| \frac{\partial W}{\partial \phi_i} \right|^2$$
- $T = T^* = \frac{1}{2}$.

[6] I. Garg, S. Mohanty, PLB,[hep-ph/1504.07725]

Inflation favourable cases

Case I: $a \neq 0$ and p=ω=0, $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

$$L_{K.E.} = \frac{(1-a^2)(\partial_\mu p)^2 + 3(\partial_\mu a)^2 + 6(1-a^2)(\partial_\mu \omega)^2}{(1-a^2)^2},$$

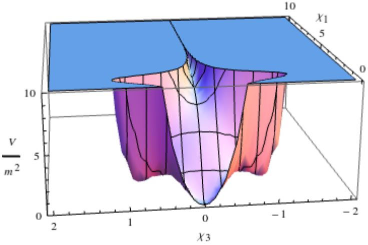
$$V = \frac{36a^4\lambda^2 + 72a^3\lambda m + 36a^2 m^2}{(1-a^2)^2}$$

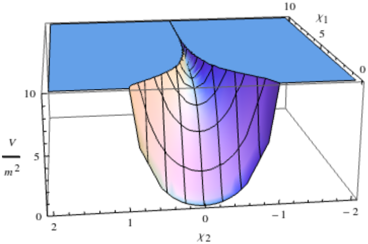
$$a = tanh[\frac{\chi_1}{\sqrt{3}}],\ p = sech[\frac{\chi_1}{\sqrt{3}}]\chi_2,\ \omega = \frac{1}{\sqrt{6}} sech[\frac{\chi_1}{\sqrt{3}}]\chi_3$$

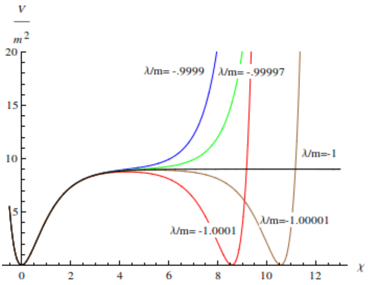
- The potential in the limit $\chi_1 \neq 0$, $\chi_2 = \chi_3$=0 is,

$$V = 36m^2(1 - e^{-\frac{2\chi_1}{\sqrt{3}}})^2$$

for λ= -m.


10
χ_1
5
0
10
5
0
$\frac{V}{m^2}$
2
1
0
−1
−2
χ_3


10
χ_1
5
0
10
5
0
$\frac{V}{m^2}$
2
1
0
−1
−2
χ_2



- $P_R = (1.610 \pm 0.01) \times 10^{-9}$ given by PLANCK5 requires value of $m = 1.311 \times 10^{-6}$ in Planck units.
- n_s = .964 and r = .002 for $N_{e-folds}$=55.
- Varying λ/m in the range (-1.0001 – -0.9999) gives n_s in the range (0.92–1.0) and r in range (0.002 –0.008).
- $SU(5) \times U(1)$ and flipped $SU(5) \times U(1)$ also give Starobinsky inflation potential but for different relation for λ and m.

No scale SUGRA and Type-I seesaw

- The superpotential and Kähler potential in this case is given by,

$$W = Y_\nu^{ij} L_i H_u N_j + \frac{1}{2} M_N^{jj} N_j N_j \quad (1)$$

$$K = -3 \ln \left(T + T^* - \frac{1}{3}(|L_i|^2 + |N_j|^2 + |H_u|^2 + ...) \right) \quad (2)$$

- D-flat direction associated with the gauge invariant LHN and NN terms.

$$\tilde{N} = \tilde{\nu} = h = \varphi = \phi e^{i\theta}; \quad \phi \geq 0, \quad \theta \in [0, 2\pi)\,, \quad (3)$$

- Freedom of choosing the generation: N_3 assuming the normal hierarchy of neutrino masses and ν_1
- With a condition Y_ν^{13}= -M_N^{33},

$$V = {M_N^{33}}^2 (1 - e^{-\frac{2\chi}{\sqrt{3}}})^2 \quad (4)$$

- The value of $P_R = (1.610 \pm 0.01) \times 10^{-9}$ given by Planck data requires value of $M_N^{33} = 1.68 \times 10^{-7}$ in Planck units.

Reheating via Instant Preheating

- Perturbative decay of inflaton is not efficient.
- Non-perturbative decay to scalars and fermions leading to preheating.
- $$T_R \sim 10^{12} - 10^{14}\,GeV$$
- Large reheat temperature leads to over abundance of gravitions.
- Such scenarios requires gravitiono mass to be O(50) TeV so that it decays before nucleosynthesis.
- The LNH flat direction inflation scenario can give rise to leptogenesis (both thermal and non thermal) through RHN and Higgs field decay.

Susy breaking in the MSGUT inflation scenario

- At temperature $<< T_R$, we assume that universe settles to the minimum of potential corresponding to MSSM symmetry.
- zero cosmological constant $\Rightarrow$ a, p, ω, $\sigma(\bar{\sigma})$ have values such that $V = \frac{|W_{\phi_i}|^2}{\Gamma^2} = 0$.
- This can be satisfied if[7]

$$a = \frac{m}{\lambda}\frac{x^2+2x-1}{1-x};\ p = \frac{m}{\lambda}\frac{x(5x^2-1)}{(1-x)^2};\ \sigma\overline{\sigma} = \frac{2m^2}{\eta\lambda}\frac{x(1-3x)(1+x^2)}{\eta(1-x)^2};$$

$$\omega = -\frac{m}{\lambda}x, \quad \text{where } 8x^3 - 15x^2 + 14x - 3 = -\frac{\lambda m_\Sigma}{\eta m}(1-x)^2$$

- $$m_{3/2}^2 = e^G = e^K |W|^2 .$$

- TeV scale gravitino mass can be achieved with field values of a, p, ω, $\sigma(\bar{\sigma})$ and tuning $|W| \approx 0$.

[7] Aulakh, Bajc, Melfo, Senjanovic, Vissani, PLB 588 (2004), arXiv:0306242

Susy breaking in the D-flat LNH inflation scenario

- The minimal superpotential and Kähler potential responsible for inflation can't give rise to SUSY breaking at the end of inflation.
- Additional Polonyi field S with

$$K(S,\bar{S}) = S\bar{S} + \frac{(S\bar{S})^2}{\Lambda^2} \quad W(S) = M^2 S + \frac{\Delta}{2}$$

- The term $(S\bar{S})^2/\Lambda^2$ with $\Lambda \ll 1$ and the fine tuning of the constant Δ $\implies$ strong stabilization of the Polonyi field and cosmological constant $\sim 10^{-120}$.
- We assume $\langle S \rangle = 0$ during inflation and at the end of inflation it settles down at some minimum and give rise to the SUSY breaking.

- The late time decay of S (after BBN) leads to "Polonyi Problem".
- This problem can be solved if,

$$m_S^2 \gg m_{3/2}^2. \tag{5}$$

- This can be achieved with $\Delta \neq 0$ and for $\Lambda \ll 1$ and the potential minimum $V_{min} \approx -3\Delta^2 + M^4$ with $S_{min} \approx \Delta/2M^2$.
- For $M^2 = \sqrt{3}\Delta$, $S_{min} = 1/2\sqrt{3}$ and the garvitino and Polonyi field masses (in Planck units) are given by,

$$m_{3/2}^2 = \Delta^2, \qquad m_S^2 = \frac{12\Delta^2}{\Lambda^2} = \frac{12 m_{3/2}^2}{\Lambda^2} \gg m_{3/2}^2, \tag{6}$$

- For $\Lambda \sim 10^{-2}$ and $\Delta \simeq 10^{-12} \sim 10^{24} GeV^2$, we obtain $m_{3/2} \sim 50$ TeV and $m_S \sim$ O(PeV).

Summary

- Starobinsky model of inflation can be derived from no-scale SUGRA SO(10) GUT for the specific intermediate symmetries of $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, $SU(5) \times U(1)$ and flipped $SU(5) \times U(1)$ gauge groups.
- However, out of favourable cases for inflation $SU(5) \times U(1)$ gives rise to monopoles after inflation and this case therefore can be ruled out from the consideration of topological defects in the cosmological evolution.
- The large reheating temperature requires gravitino mass of O(50 TeV).
- Type-I seesaw inflation scenario requires additional fields in the hidden sector whereas the MSGUT inflation scenario needs fine tuning of visible sector couplings to break SUSY.
- Type-I seesaw inflation scenario requires realistic Yukawa to achieve inflation along with fitting to the neutrino oscillation data.

THANKS