No-scale Supergravity Hybrid Inflation with Broken R-symmetry

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Outline

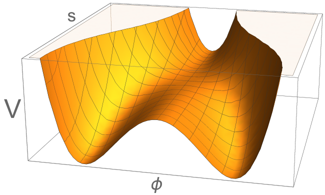
Supergravity inflation model building

- Slow-roll conditions: the eta problem
  Shift symmetry - R-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.
  - $DW = 0, W = 0$ at the vacuum for SUSY case
  - No-scale supergravity
- 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,.....

Supersymmetric Hybrid Inflation

- The most general form of a superpotential that is renormalizable and respects $U(1)_R$ symmetry

$$W = \kappa S(\phi_1\phi_2 - M^2)$$



- True vacuum: $\langle\phi_1\phi_2\rangle = M^2$, $\langle S\rangle = 0$
  - D-flat direction $|\phi_1| = |\phi_2|$. During inflation $\phi_1 = \phi_2 = 0$ and universe is dominated by constant vacuum energy $\kappa^2 M^4$.
  - CW 1-loop correction provides a slope for S roll down.

R-symmetry - important advantages:

- preventing higher order terms in S
- supergravity corrections to the inflaton mass (no η-problem)
- Low energy phenomenology ....

No-scale Supergravity Inflation

- No-scale supergravity offers a natural solution to the η-problem, and can yield an inflation potential with a plateau adequate for slow rolling due to the noncompact $SU(N,1)/SU(N)\times U(1)$ no-scale symmetry. No R-symmetry. SUSY can be broken at Minkowski vacuum.
- The model of Ellis-Nanopoulos-Olive (ENO) 2013, relies on the no-scale symmetry $SU(2,1)/SU(2)\times U(1)$

$$W = \frac{\mu}{2}S^2 - \frac{\lambda}{3}S^3,$$
$$K = -3\log\left[T+\bar{T}-\tfrac{|S|^2}{3}\right]$$

- The superpotential doesn't respect R-symmetry and the resulting inflation potential for canonical scalar field x is the Starobinsky potential for $\hat{\mu}=\lambda$

$$V = \frac{\hat{\mu}^2}{4}\left(1-e^{-\sqrt{2/3}x}\right)^2 \ , \ \hat{\mu}\equiv\frac{\mu}{\sqrt{6\tau_0}}$$

Hybrid Inflation in No-scale Supergravity [1]

A renormalizable superpotential with non-exact R-symmetry, and no-scale structure for the Kähler potential

$$W = \kappa\, S\left(\phi_1\,\phi_2 - M^2\right) - \tfrac{\mu}{2} S^2 + \tfrac{\lambda}{3} S^3$$
$$K = -3\log\left[T + \bar{T} - \tfrac{|S|^2}{3} - \tfrac{|\phi_1|^2}{3} - \tfrac{|\phi_2|^2}{3}\right]$$

- D-flat direction $|\phi_1| = |\phi_2|$, and SUSY vacuum

$$\langle S \rangle = 0 \;\&\; \langle \phi_1 \phi_2 \rangle = M^2$$

- During inflation $\phi_1 = \phi_2 = 0$, and the effective potential

$$V_{inf} = \frac{1}{\left(2\tau_0 - \frac{|S|^2}{3}\right)^2} \left|\kappa M^2 + \mu S - \lambda S^2\right|^2,$$

[1] A.M. (2021)

Hybrid Inflation in No-scale Supergravity

The squared mass matrix contains a mixing between the inflaton and the waterfall fields

$$\mathcal{M}^2 = \begin{pmatrix} \frac{27\tau_0^2\left(2M^2\kappa^2+\mu^2\right)}{2(3\tau_0-M^2)^3} & -\frac{27\sqrt{6}M\tau_0^{3/2}\kappa\mu}{2(3\tau_0-M^2)^{7/2}} \\ -\frac{27\sqrt{6}M\tau_0^{3/2}\kappa\mu}{2(3\tau_0-M^2)^{7/2}} & \frac{81\tau_0\, M^2\kappa^2}{(3\tau_0-M^2)^4} \end{pmatrix}$$

Hybrid Inflation in No-scale Supergravity

- Field redefinitions ⇒ canonical kinetic terms

$$S = \sqrt{6\tau_0}\,\tanh\left(\frac{\chi}{\sqrt{3}}\right)\,, \qquad \chi = \frac{x + i\,y}{\sqrt{2}}$$

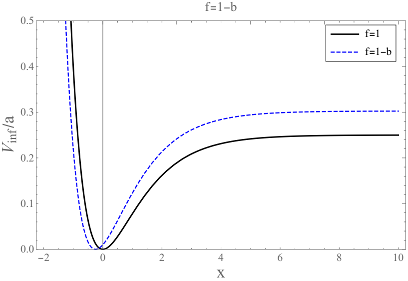
$$V_{inf} = \frac{a}{4}\left((1+b) + (b-1)\cosh\left(\sqrt{\frac{2}{3}}x\right) + f\sinh\left(\sqrt{\frac{2}{3}}x\right)\right)^2$$

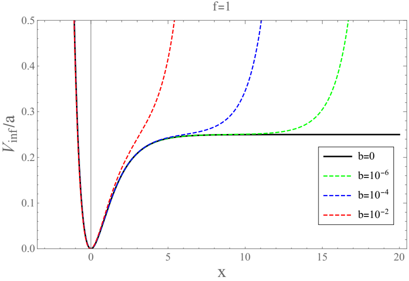
$$a = |3\lambda|^2\,, \quad b = \frac{\kappa\,\hat{M}^2}{\lambda}\,, \quad f = \frac{\hat{\mu}}{\lambda}$$

Hybrid Inflation in No-scale Supergravity

- Asymptotically flat potential arises in the limit $f = 1 - b$

$$V_{inf}\Big|_{f \to 1-b} = \frac{a}{4}\left((b+1) + (b-1)e^{-\sqrt{\frac{2}{3}}x}\right)^2$$



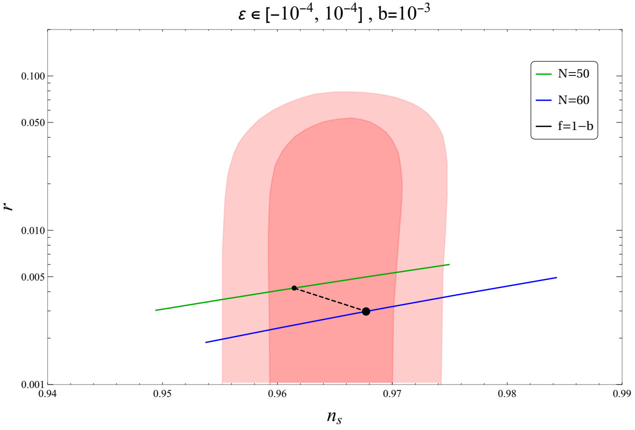


Hybrid Inflation in No-scale Supergravity

- Inflation observables : For $f = 1 - b$

$$ns \simeq 1 - \frac{2}{N} - \frac{3}{N^2}, \quad r \simeq \frac{12}{N^2}, \quad A_S \sim 2 \times 10^{-9} \text{ for } a \sim 10^{-10}$$

- For $f = 1 - b + \varepsilon$



FGUT Model as a Realistic Example and Reheating

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

$$\begin{aligned} W \;&=\; \kappa S\left(\mathbf{10}_H^{\alpha\beta}\,\overline{\mathbf{10}}_{H\alpha\beta} - M^2\right) - \frac{\mu}{2}\,S^2 + \frac{\lambda}{3}\,S^3 + \lambda_1\,\epsilon_{\alpha\beta\gamma\delta\zeta}\,\mathbf{10}_H^{\alpha\beta}\,\mathbf{10}_H^{\gamma\delta}\,\mathbf{5}_H^{\zeta} \\ &\quad + Y_u\,\bar{\mathbf{5}}_{H_u\alpha}\,\mathbf{10}_F^{\alpha\beta}\,\bar{\mathbf{5}}_{F\beta} + Y_d\,\epsilon_{\alpha\beta\gamma\delta\zeta}\,\mathbf{10}_F^{\alpha\beta}\,\mathbf{10}_F^{\gamma\delta}\,\mathbf{5}_{H_d}^{\zeta} + Y_e\,\mathbf{5}_{H_d}^{\lambda}\,\bar{\mathbf{5}}_{F\lambda}\,\mathbf{1}_F \end{aligned}$$

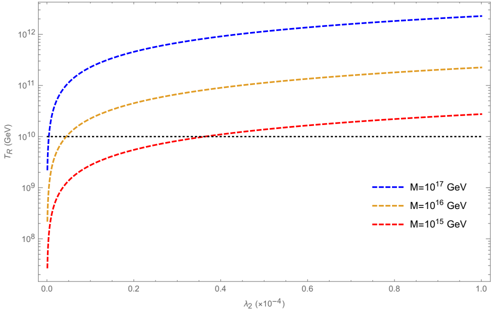
- FGUT symmetry allows the term $\dfrac{\lambda_2}{M_P}\,\mathbf{10}_F\,\mathbf{10}_F\,\overline{\mathbf{10}}_H\,\overline{\mathbf{10}}_H$, that gives rise to right-handed neutrino masses and allows for decay channels for the inflaton to right-handed neutrinos and sneutrinos.

Reheating and neutrino masses in FGUT model

$$\mathcal{L}_{int} = \frac{\lambda_2 M}{M_P}\, \bar{\nu}_H^c\, \nu^c\, \nu^c + \left(\frac{2\kappa\lambda_2 M^2}{M_P}\, S\, \tilde{\nu}^{c\,*}\, \tilde{\nu}^{c\,*} + h.c. \right)$$

$$T_R \approx \frac{(8\pi)^{1/4}}{7}\, (\Gamma\, M_p)^{1/2}\,,$$

- $M \sim 10^{15}$ GeV and $\lambda_2 \sim 0.35 \times 10^{-4}$, $M_{\nu^c} < 10^8$ GeV, $\sin\beta \sim \mathcal{O}(1)$ and $Y_u < 10^{-3}$ $\Rightarrow$ $m_\nu = \dfrac{Y_u^2 v^2 \sin^2\beta}{M_{\nu^c}} \sim 0.1$ eV



Tribid Inflation Model in No-scale Supergravity[2]

	S_1	S_2	ϕ_1	ϕ_2	S	N
$U(1)_{B-L}$	1	-1	2	-2	0	-1
R	1	1	0	0	2	-1
Z_3	ω^2	ω	ω	ω^2	1	ω

$$W_{inf} = \kappa_1 S\left(\phi_1\phi_2 - \mu M_P\right) + \kappa_2\, S_1 S_2\left(\frac{\phi_1\phi_2}{M_P} - \mu\right) + \frac{\lambda_1}{M_P}(S_1 S_2)^2 + \frac{\lambda_2}{M_P} S^2 S_1 S_2$$

$$K = -3M_P^2 \log\left[\frac{T+\overline{T}}{M_P} - \frac{|S|^2}{3M_P^2} - \frac{|S_1|^2}{3M_P^2} - \frac{|S_2|^2}{3M_P^2} - \frac{|\phi_1|^2}{3M_P^2} - \frac{|\phi_2|^2}{3M_P^2}\right]$$

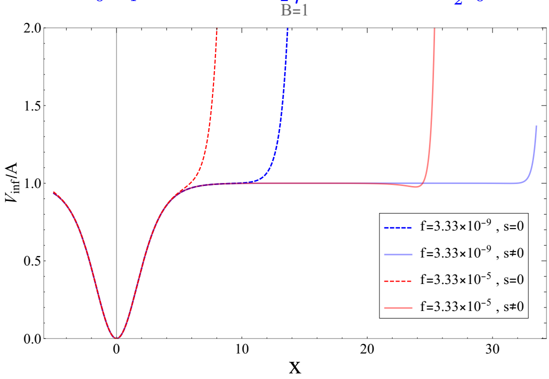
- $S_{1,2}$ contains the inflaton
- $S_{1,2}$ contribute to inverse seesaw mechanism
- $\phi_{1,2}$ are the waterfall fields
- S is a driving field and flattens the inflation potential

[2] A.M. (2021)

Tribrid Inflation Model in No-scale Supergravity

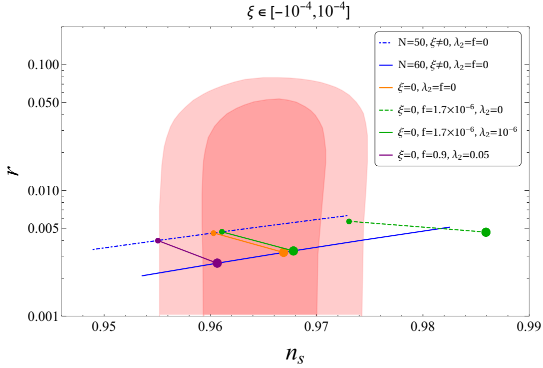
$$V = A\cosh^4\left(\frac{x}{\sqrt{6}}\right)\left[B^2\tanh^6\left(\frac{x}{\sqrt{6}}\right) - 2B\tanh^4\left(\frac{x}{\sqrt{6}}\right) + \tanh^2\left(\frac{x}{\sqrt{6}}\right) + f\right]$$

$$A = \frac{3\mu^2\kappa_2^2}{2\tau_0 M_P}\,, \qquad B = \frac{6\lambda_1\tau_0}{\kappa_2\,\mu}\,, \qquad f = \frac{\kappa_1^2 M_P}{6\kappa_2^2\tau_0}$$



Observables

λ_2	f	μ	κ_1	κ_2	λ_1	τ_0	M
$0 - 10^{-6}$	1.7×10^{-6}	2.8×10^{-6}	10^{-3}	0.9	4.3×10^{-6}	0.1	1.6×10^{-3}
		2.8×10^{-5}	10^{-2}		4.3×10^{-7}	10	5.3×10^{-3}
$0.05 - 0.9$	0.9	4×10^{-6}	0.95	0.9	3×10^{-6}	0.2	2×10^{-3}
		3.6×10^{-3}	0.1	0.01	3×10^{-7}	20	6×10^{-2}



SUSY breaking, Reheating and Neutrino Masses

$$W_\nu = Y_\nu L H_u N + Y_S\, S\, N\, S_1 + \frac{\lambda_3}{M_P}\, S\, \phi_1\, N\, S_2 + \left[\frac{\lambda_2}{M_P} S^2 + \kappa_2 \left(\frac{\phi_1\phi_2}{M_P} - \mu\right)\right] S_1 S_2$$

- SUSY breaking effects results in shifts in the minima

$$\langle S \rangle \simeq \frac{m_{3/2}}{\kappa_1}\ , \qquad \langle|\phi_1|\rangle = \langle|\phi_2|\rangle \simeq M \left(1 - \frac{m_{3/2}^2}{\kappa_1^2 M^2}\right)$$

- Neutrino masses Lagrangian

$$\mathcal{L}_\nu = m_D\, \bar{\nu}_L\, N^c + M_{R_1}\, \bar{N}^c\, S_1^c + M_{R_2}\, \bar{N}^c\, S_2^c + \mu_S\, \bar{S_1}^c\, S_2^c + h.c.$$

$$\begin{aligned} m_D &= Y_\nu\, v \sin(\beta)\, , \qquad M_{R_1} = \frac{Y_S\, m_{3/2}}{\kappa_1}\, , \qquad M_{R_2} = \frac{\lambda_3\, m_{3/2}\, M}{\kappa_1\, M_P}\, , \\ \mu_S &= \frac{\lambda_2}{M_P} \langle S \rangle^2 + \frac{\kappa_2}{M_P}\left[\langle \phi_1\phi_2 \rangle - M^2\right] \\ &= \frac{m_{3/2}^2}{\kappa_1^2\, M_P}\left[\lambda_2 - \kappa_2 + \frac{\kappa_2\, m_{3/2}^2}{2\kappa_1^2\, M^2}\right] \end{aligned}$$

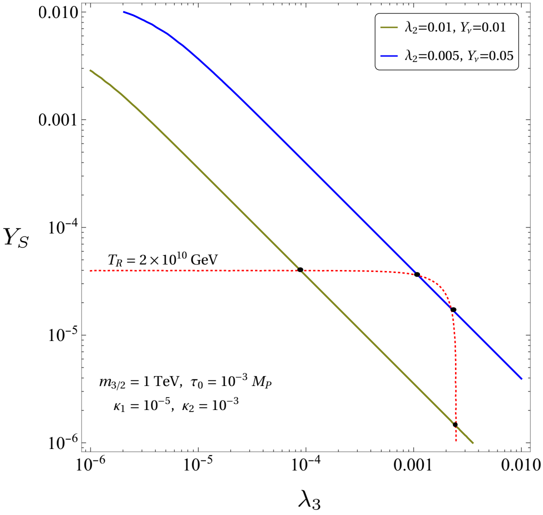
SUSY breaking, Reheating and Neutrino Masses

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 & 0 \\ m_D & 0 & M_{R_1} & M_{R_2} \\ 0 & M_{R_1} & 0 & \mu_S \\ 0 & M_{R_2} & \mu_S & 0 \end{pmatrix}$$

$$\begin{aligned} m_{\nu_l} &\simeq \frac{m_D^2\,\mu_S}{2M_{R_1}M_{R_2}}\,, \\ m_{\nu_1} &\simeq \frac{\mu_S\left(-\frac{m_D^2}{2M_{R_2}} - 2M_{R_2}\right)}{M_{R_1}} \sim \mu_S\,, \\ m_{\nu_{2,3}} &\simeq \pm\left(M_{R_1} + \frac{m_D^2 + M_{R_2}^2}{2M_{R_1}}\right) + \frac{M_{R_2}\mu_S}{M_{R_1}} \sim \pm\left(M_{R_1} + M_{R_2}\right) \end{aligned}$$

$m_{3/2}$	λ_2	λ_3	κ_1	κ_2	Y_ν	Y_S	$\lvert m_{\nu_1}\rvert$	$\lvert m_{\nu_{2,3}}\rvert$
10^3	0.008	0.002	10^{-5}	10^{-3}	0.05	3×10^{-5}	3×10^{-5}	4.4×10^3
0.1	0.9	0.4	10^{-7}	0.1	0.9	0.01	2.1×10^{-7}	1.06×10^4
10^5	0.1	0.01	0.01	0.01	0.5	0.0032	6.6×10^{-7}	3.21×10^4

SUSY breaking, Reheating and Neutrino Masses



Thank you