Supersymmetric & Mu-Term Hybrid Inflation

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Inflationary Cosmology

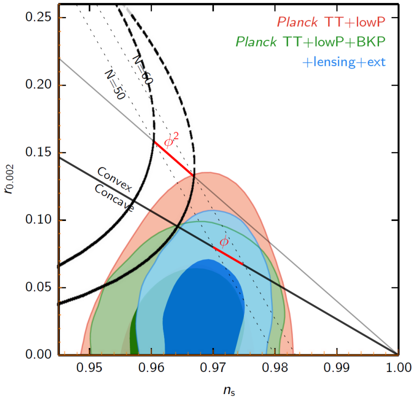
[Guth, Linde, Albrecht & Steinhardt, Starobinsky, Mukhanov, Hawking, . . .]

Successful Primordial Inflation should:

- Explain flatness, isotropy;
- Provide origin of $\frac{\delta T}{T}$;
- Offer testable predictions for n_s, r, $dn_s/d\ln k$;
- Recover Hot Big Bang Cosmology;
- Explain the observed baryon asymmetry;
- Offer plausible CDM candidate;

ϕ^2 Inflation

Radiatively Corrected ϕ^2 Potential:



n_s vs. r for radiatively corrected ϕ^2 potential, superimposed on Planck and Planck+BKP 68% and 95% CL regions taken from arXiv:1502.01589. The dashed portions are for $\kappa < 0$. N is taken as 50 (left curves) and 60 (right curves).

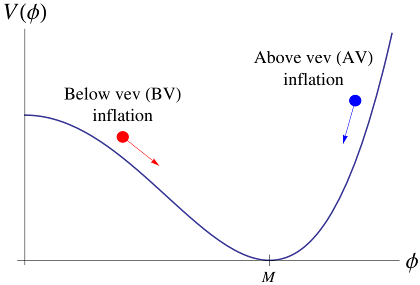
Tree Level Gauge Singlet Higgs Inflation

[Kallosh and Linde, 07; Rehman, Shafi and Wickman, 08]

- Consider the following Higgs Potential:

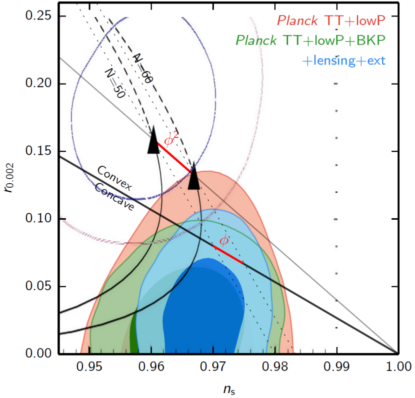
$$V(\phi) = V_0 \left[1 - \left(\frac{\phi}{M}\right)^2\right]^2 \quad \longleftarrow \text{(tree level)}$$

Here ϕ is a gauge singlet field.



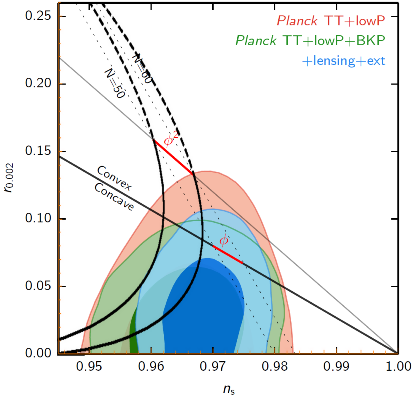
- WMAP/Planck data favors BV inflation ($r \lesssim 0.1$).

Higgs Potential:



n_s vs. r for Higgs potential, superimposed on Planck and Planck+BKP 68% and 95% CL regions taken from arXiv:1502.01589. The dashed portions are for $\phi > v$. N is taken as 50 (left curves) and 60 (right curves).

Coleman–Weinberg Potential:



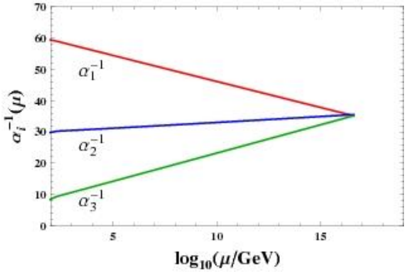
n_s vs. r for Coleman–Weinberg potential, superimposed on Planck and Planck+BKP 68% and 95% CL regions taken from arXiv:1502.01589. The dashed portions are for $\phi > v$. N is taken as 50 (left curves) and 60 (right curves).

Coleman–Weinberg Potential:

n_s $(N = 50)$	r $(N = 50)$	n_s $(N = 60)$	r $(N = 60)$
0.935	0.00112	0.946	0.00112
0.952	0.026	0.961	0.0254
0.958	0.0498	0.966	0.0471
0.961	0.0712	0.968	0.0652
0.961	0.141	0.968	0.119
0.96	0.161	0.967	0.134
0.956	0.208	0.964	0.171
0.951	0.256	0.959	0.211
0.94	0.324	0.95	0.27
0.939	0.33	0.949	0.276
0.94	0.32	0.95	0.268

Gauge coupling unification

$$(\mathbf{3},\mathbf{2})^f{}_{1/6} + (\bar{\mathbf{3}},\mathbf{2})^f{}_{-1/6} + (\bar{\mathbf{3}},\mathbf{1})^f{}_{1/3} + (\mathbf{3},\mathbf{1})^f{}_{-1/3}$$



$$M_{GUT} = 3 \times 10^{16}\ \mathrm{GeV}$$

$$\alpha_{GUT}^{-1} \approx 34$$

$$M_f \approx 2\ TeV$$

GUT Inflation & Proton Decay

Coleman-Weinberg Potential		Higgs Potential	
$M_X \sim 2\, V_0^{1/4}$(GeV)	$\tau(p \to \pi^0 e^+)$ (years)	$M_X \sim V_0^{1/4}$(GeV)	$\tau(p \to \pi^0 e^+)$ (years)
5.0×10^{15}	1.8×10^{34}	1.0×10^{16}	2.8×10^{35}
1.0×10^{16}	2.8×10^{35}	1.2×10^{16}	5.8×10^{35}
1.2×10^{16}	5.8×10^{35}	1.4×10^{16}	1.1×10^{36}
1.8×10^{16}	2.9×10^{36}	1.6×10^{16}	1.8×10^{36}
2.2×10^{16}	6.6×10^{36}	1.8×10^{16}	2.9×10^{36}
2.7×10^{16}	1.5×10^{37}	2.1×10^{16}	5.5×10^{36}
3.5×10^{16}	4.2×10^{37}	2.4×10^{16}	9.3×10^{36}
6.0×10^{16}	3.6×10^{38}	2.9×10^{16}	2.0×10^{37}

Table: Superheavy gauge bosons masses and corresponding proton lifetimes with $\alpha_G = \frac{1}{35}$ in the CW and Higgs models. Note that since the lifetime depends only on M_X, the results shown here apply equally well to the BV and AV branches in each model.

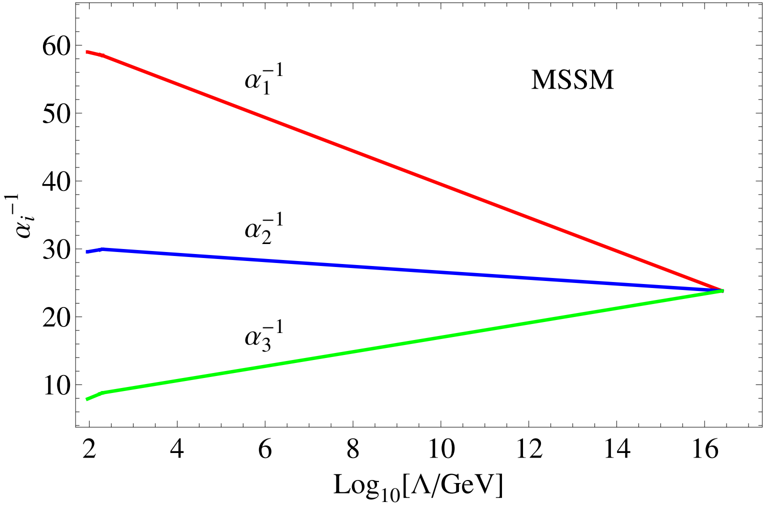
- Where does ϕ come from?
    1) Associated with spontaneous breaking of global $U(1)_{B-L}$, $U(1)_X$ in $SU(5)$, or $U(1)_L$ (majoran dark matter);
    2) Breaks gauged $U(1)_{B-L}$ (in this case B-L gauge coupling should be $\lesssim 10^{-3}$);
    3) Associated with $U(1)_{PQ}$ if we employ non-minimal coupling to gravity.
- Topological Defects:
  Cosmic strings and magnetic monopoles may survive inflation if the symmetry breaking scale is comparable to H (Hubble constant) during inflation.
- Example: $SO(10) \to SU(4)_C \times SU(2)_L \times SU(2)_R \to SU(3)_C \times SU(2)_L \times U(1)_Y$.
  Second breaking yields monopoles carrying two units of Dirac magnetic charge.

Supersymmetry

- Resolution of the gauge hierarchy problem
- Predicts plethora of new particles which LHC should find
- Unification of the SM gauge couplings at $M_{GUT} \sim 2 \times 10^{16}$ GeV
- Cold dark matter candidate (LSP)
- Radiative electroweak breaking
- String theory requires supersymmetry (SUSY)

Alas, SUSY not yet seen at LHC

Why Supersymmetry?



SUSY Higgs (Hybrid) Inflation

[Dvali, Shafi, Schaefer; Copeland, Liddle, Lyth, Stewart, Wands '94]

[Lazarides, Schaefer, Shafi '97][Senoguz, Shafi '04; Linde, Riotto '97]

- Attractive scenario in which inflation can be associated with symmetry breaking $G \longrightarrow H$
- Simplest inflation model is based on

$$W = \kappa\, S\, (\Phi\, \overline{\Phi} - M^2)$$

$S =$ gauge singlet superfield, $(\Phi\,,\overline{\Phi})$ belong to suitable representation of G

- Need $\Phi\,,\overline{\Phi}$ pair in order to preserve SUSY while breaking $G \longrightarrow H$ at scale $M \gg$ TeV, SUSY breaking scale.
- R-symmetry

$$\Phi\,\overline{\Phi} \rightarrow \Phi\,\overline{\Phi}, \;\; S \rightarrow e^{i\alpha}\, S, \;\; W \rightarrow e^{i\alpha}\, W$$

$\Rightarrow \quad W$ is a unique renormalizable superpotential

- Some examples of gauge groups:

$G = U(1)_{B-L}$, (Supersymmetric superconductor)

$G = SU(5) \times U(1), \quad (\Phi = 10), \quad$ (Flipped $SU(5)$)

$G = 3_c \times 2_L \times 2_R \times 1_{B-L}, \; (\Phi = (1, 1, 2, +1))$

$G = 4_c \times 2_L \times 2_R, \; (\Phi = (\overline{4}, 1, 2)),$

$G = SO(10), \; (\Phi = 16)$

- At renormalizable level the SM displays an ‘accidental’ global $U(1)_{B-L}$ symmetry.

- Next let us ‘gauge’ this symmetry, so that $U(1)_{B-L}$ is now promoted to a local symmetry. In order to cancel the gauge anomalies, one may introduce 3 SM singlet (right-handed) neutrinos.

This has several advantages:

- See-saw mechanism is automatic and neutrino oscillations can be understood.

- RH neutrinos acquire masses only after $U(1)_{B-L}$ is spontaneously broken; Neutrino oscillations require that RH neutrino masses are $\lesssim 10^{14}\mathrm{GeV}$.

- RH neutrinos can trigger leptogenesis after inflation, which subsequently gives rise to the observed baryon asymmetry;

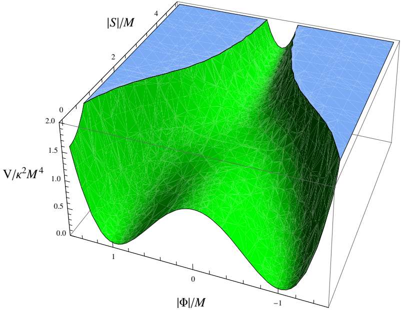
- Last but not least, the presence of local $U(1)_{B-L}$ symmetry enables one to explain the origin of Z_2 'matter' parity of MSSM. (It is contained in $U(1)_{B-L} \times U(1)_Y$, if $B-L$ is broken by a scalar vev, with the scalar carrying two units of $B-L$ charge.)

- Tree Level Potential

$$V_F = \kappa^2 \left(M^2 - |\Phi^2|\right)^2 + 2\kappa^2 |S|^2 |\Phi|^2$$

- SUSY vacua

$$|\langle\overline{\Phi}\rangle| = |\langle\Phi\rangle| = M, \ \langle S\rangle = 0$$



Take into account radiative corrections (because during inflation $V \neq 0$ and SUSY is broken by $F_S = -\kappa\, M^2$)

- Mass splitting in $\Phi - \overline{\Phi}$

$$m_{\pm}^2 = \kappa^2\, S^2 \pm \kappa^2\, M^2, \quad m_F^2 = \kappa^2\, S^2$$

- One-loop radiative corrections

$$\Delta V_{\text{1loop}} = \frac{1}{64\pi^2}\text{Str}[\mathcal{M}^4(S)(\ln\frac{\mathcal{M}^2(S)}{Q^2} - \frac{3}{2})]$$

- In the inflationary valley $(\Phi = 0)$

$$V \simeq \kappa^2\, M^4 \left(1 + \frac{\kappa^2 \mathcal{N}}{8\pi^2} F(x)\right)$$

where $x = |S|/M$ and

$$F(x) = \frac{1}{4}\left(\left(x^4+1\right)\ln\frac{\left(x^4-1\right)}{x^4} + 2x^2\ln\frac{x^2+1}{x^2-1} + 2\ln\frac{\kappa^2 M^2 x^2}{Q^2} - 3\right)$$

Tree level + radiative corrections + minimal Kähler potential yield:

$$n_s = 1 - \frac{1}{N} \approx 0.98.$$

$\delta T/T$ proportional to M^2/M_p^2, where M denotes the gauge symmetry breaking scale. Thus we expect $M \sim M_{GUT}$ for this simple model.

Since observations suggest that n_s lie close to 0.97, there are at least two ways to realize this slightly lower value:

- include soft SUSY breaking terms, especially a linear term in S;
- employ non-minimal Kähler potential.

Full Story

Also include supergravity corrections + soft SUSY breaking terms

- The minimal Kähler potential can be expanded as

$$K = |S|^2 + |\Phi|^2 + \left|\overline{\Phi}\right|^2$$

- The SUGRA scalar potential is given by

$$V_F = e^{K/m_p^2}\left(K_{ij}^{-1} D_{z_i} W D_{z_j^*} W^* - 3m_p^{-2}|W|^2\right)$$

where we have defined

$$D_{z_i}W \equiv \frac{\partial W}{\partial z_i} + m_p^{-2}\frac{\partial K}{\partial z_i}W;\; K_{ij} \equiv \frac{\partial^2 K}{\partial z_i \partial z_j^*}$$

and $z_i \in \{\Phi, \overline{\Phi}, S, ...\}$

[Senoguz, Shafi '04; Jeannerot, Postma '05]

- Take into account sugra corrections, radiative corrections and soft SUSY breaking terms:

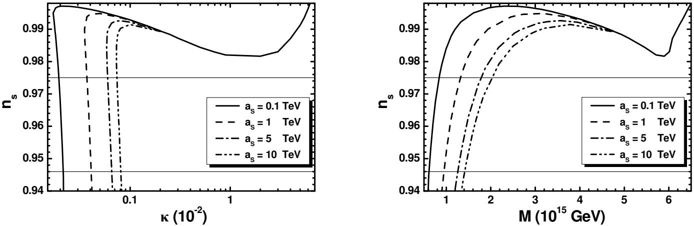
$$V \simeq \kappa^2 M^4 \left(1 + \left(\frac{M}{m_p}\right)^4 \frac{x^4}{2} + \frac{\kappa^2 \mathcal{N}}{8\pi^2} F(x) + a_s \left(\frac{m_{3/2} x}{\kappa M}\right) + \left(\frac{m_{3/2} x}{\kappa M}\right)^2\right)$$

where $a_s = 2\,|2 - A|\cos[\arg S + \arg(2 - A)]$, $x = |S|/M$ and $S \ll m_P$.

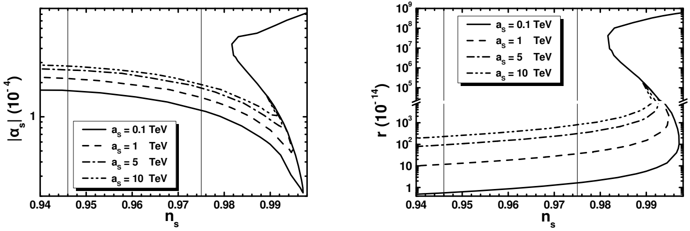
Note: No 'η problem' with minimal (canonical) Kähler potential !

Results

[Pallis, Shafi, 2013; Rehman, Shafi, Wickman, 2010]



(a) (b)



(a) (b)

Minimal W and Non-Minimal K

$$\mathcal{K} = |S|^2 + |\Phi|^2 + |\overline{\Phi}|^2 + \kappa_S \frac{|S|^4}{4m_p^2} + \kappa_{S\Phi} \frac{|S|^2|\Phi|^2}{m_p^2} + \kappa_{S\overline{\Phi}} \frac{|S|^2|\overline{\Phi}|^2}{m_p^2} + \kappa_{SS} \frac{|S|^6}{6m_p^4} + \cdots$$

$$V = V_1^{\text{non-min}}(\phi = 0) \simeq \kappa^2 M^4 \left(1 - \kappa_S \frac{S_R^2}{2m_p^2} + \gamma_S \frac{S_R^4}{8m_p^4} + \cdots\right) + \Delta\mathcal{V}_{1loop}$$

$$n_s \simeq 1 - 2\kappa_S - 2\delta = 0.98 - 2\kappa_S$$

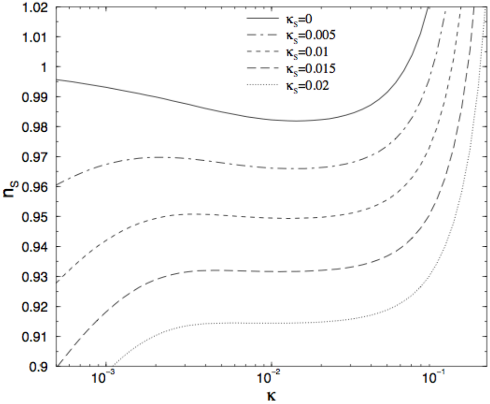


Figure 5: Non-Minimal Kähler potential: predicted value of the spectral index n_s depending on the value of the coupling κ, for different values of κ_S. We have taken $\mathcal{N} = 1$.

$U(1)_R$ symmetry prevents a direct μ term but allows the superpotential coupling

$$\lambda H_u H_d S$$

Since $\langle S \rangle$ acquires a non-zero VEV $\propto m_{3/2}$ from supersymmetry breaking, the MSSM μ term of the desired magnitude is realized.

- A U(1) R-symmetry yields the following unique renormalizable superpotential:

$$W = S(\kappa\overline{\Phi}\Phi - \kappa M^2 + \lambda H_u H_d).$$

- Include SUSY breaking/SUGRA, the inflationary potential is

$$V(\phi) = m^4\left(1 + A\ln\left[\frac{\phi}{\phi_0}\right]\right) - 2\sqrt{2}m_G m^2\phi,$$

$$\phi = \sqrt{2}\text{Re}[S],\ m \equiv \sqrt{\kappa}M,$$

$$A = \frac{1}{4\pi^2}\left(\lambda^2 + \frac{N_\Phi}{2}\kappa^2\right).$$

- Successful inflation/gauge symmetry breaking requires $\lambda > \kappa$.

critical points!!

μ-Term Inflation

- The MSSM μ-term

$$\mu = \frac{\lambda}{\kappa} m_G \equiv \gamma m_G.$$

- One finds

$$n_s \simeq 1 - \frac{2}{N} f(B),\ B = \frac{2\sqrt{2}\, m_G\, \phi_0}{A\, m^2}$$

- For N_0=60:
  1) $B = 0 \Rightarrow f(B) = 1/2 \Rightarrow n_s \simeq 0.98$.
  2) $B = 0.7 \Rightarrow f(B) = 1.03 \Rightarrow n_s \simeq 0.966$.

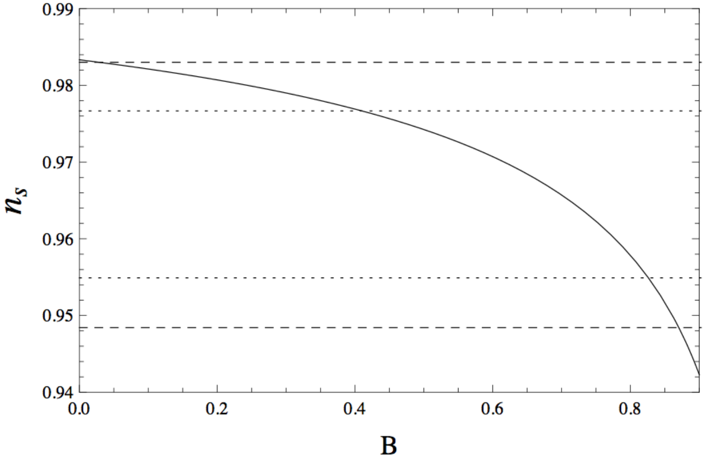


Figure: Spectral index n_s vs. B. The region between the two dotted (dashed) lines corresponds to 1σ (2σ) limit obtained by Planck 2015.

Inflaton Decay:

- The decay width is estimated to be

$$\Gamma(\phi \to \tilde{H}_u \tilde{H}_d) = \frac{\lambda^2}{8\pi} m_\phi.$$

- Lower bound:

$$T_r \geq 3.2 \times 10^{11}\ \text{GeV}.$$

- Cosmology with gravitinos:
  1) LSP gravitino not realized.
  2) If m_G is sufficiently large, LSP is still in thermal equilibrium when inflaton/gravitino decay

$$\Rightarrow m_G \gtrsim \left(4.6 \times 10^7\ \text{GeV}\right) \left(\frac{m_{\text{LSP}}}{2\text{TeV}}\right)^{2/3}.$$

The scenario suggests split SUSY

$m_0 \sim m_G \sim \mu(\Rightarrow \tan\beta \approx 2, m_h \approx 125\text{GeV})$

$M_{1/2} \sim$ TeV $\Rightarrow$ Wino dark matter

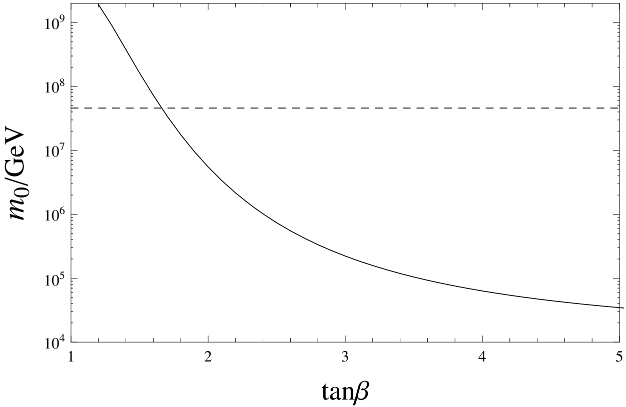


Figure: Soft scalar mass m_0 as a function of $\tan\beta$.

Summary

- If $r \sim 0.1 - 0.02$, then inflation models based on the Higgs / Coleman-Weinberg potentials can provide simple / realistic frameworks for inflation, with minimal coupling to gravity.
- There is a lower bound on H (Hubble constant) in these models. This is important for topological defects in GUT models involving intermediate scales.
- If $r \lesssim 0.01$, then supersymmetric hybrid inflation models are especially interesting. These work with inflaton field values below M_{Planck}, and supergravity corrections are under control. The simplest versions employ TeV scale SUSY, and hopefully LHC 14 will find it.
- μ-term assisted hybrid inflation consistent with Wino dark matter and a 125 GeV SM-like Higgs. Sparticles well beyond reach of LHC? Gluino mass in the TeV range.