Radiative Lifting of Flat Directions of the MSSM during Inflation

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BG, Phys. Rev. D **74** (2006) 043507, [arXiv:hep-th/0604166]
BG, Nucl. Phys. B. **784** (2007) 118, [arXiv:hep-ph/0612011]
BG, C. Pallis and A. Pilaftsis, JHEP **0612** (2006) 038, [arXiv:hep-ph/0605264]

Outline

- Flat directions of the MSSM are lifted during inflation.
- Usually considered origins of lifting:
  - SUGRA corrections
  - nonrenormalizable superpotential terms
  - both contributions in general unknown or arbitrary

In this talk:

There are calculable corrections of competitive magnitude to the aforementioned ones.
Two types of radiative corrections:

- a generic in the curved de Sitter background
- a particular one, arising in F-term hybrid inflation

MSSM Flat Directions

- Combination of Higgs, squark and slepton scalar fields which
  - are gauge invariant (D-flat).
  - have vanishing potential arising from superpotential (F-flat).
- For example $u\,d\,d$ may contain

$$\tilde{t}_R = \begin{pmatrix} \varphi \\ 0 \\ 0 \end{pmatrix} , \quad \tilde{s}_R = \begin{pmatrix} 0 \\ \varphi \\ 0 \end{pmatrix} , \quad \tilde{d}_R = \begin{pmatrix} 0 \\ 0 \\ \varphi \end{pmatrix} .$$

  These compose a massless scalar field as

$$\Phi = \frac{1}{\sqrt{3}} \left(\tilde{t}_R + \tilde{s}_R^* + \tilde{d}_R^* \right) .$$

- $\phi = |\varphi|$ is the canonically normalized modulus field and $V(\phi) \equiv 0$.

Flat Directions in Cosmology

- There is a large number of flat directions, giving rise to exhaustively studied scenarios.
  - Affleck-Dine baryogenesis (Affleck & Dine (1985)).
  - Baryonic isocurvature perturbations (Enqvist & McDonald (1999)).
  - Q-balls (Coleman (1985)).
  - Curvaton Scenario (Enqvist & Sloth; Lyth & Wands (2002)).
  - Thermal history of the Universe (Mazumdar, Allahverdi (2005)).
- During inflation, they can acquire large VEVs.
- VEV is determined by lifting contributions that break the flatness.
- Critical mass for overdamped regime: $m^2 = \frac{9}{16}H^2$.

Non-calculable contributions to the lifting

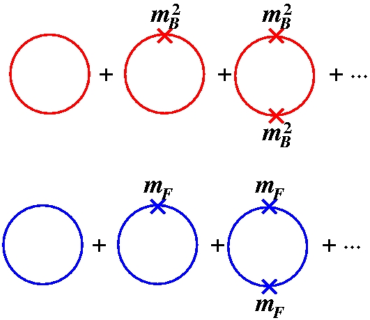
SUGRA (Dine, Randall, Thomas (1995))

- For $F \neq 0$, typical mass terms of order H^2.
- Depend on the unknown Kähler potential.
- These corrections are absent or highly suppressed when imposing certain symmetries on the Kähler potential. (Gaillard, Murayama & Olive (1995))
- Also absent in D-term inflation.

Nonrenormalizable superpotential terms (see *e.g.* Ghergetta, Kolda, Martin (1996))

- Higher dimensional, Planck scale suppressed superpotential terms.
- Purpose: Stabilizing the potential for VEVs towards the Planck scale.

One-Loop Effective Potentials



- Sum of all mass insertions.
- VEV ϕ of the flat direction generates masses
  - *via* the Yukawa couplings h from the superpotential.
  - *via* the gauge coupling g (super-Higgs mechanism).
- NB: These corrections vanish when SUSY exact (nonrenormalization).

Yukawa Contributions

Bosons:
Higgs/squark/sfermion mixing state
Fermions:
higgsino/quark/lepton mixing state
$\mathrm{tr}\, m_B^2 = \mathrm{tr}\, m_F^2 \propto h^2 \phi^2$

Gauge Contributions

Bosons:
gauge bosons,
D-term scalars
Fermions:
gaugino/higgsino mixing state
$\mathrm{tr}\, m_B^2 = \mathrm{tr}\, m_F^2 \propto g^2 \phi^2$

SUSY breaking during inflation

- Breaking through the curved de Sitter background.
  BG, Phys. Rev. D **74** (2006) 043507, [arXiv:hep-th/0604166]
  BG, Nucl. Phys. B. (in press), [arXiv:hep-ph/0612011]
- The ususal mechanism of spontaneous SUSY breaking:
  For certain models, the MSSM fields couple via loops to the vacuum energy driving inflation. F-term hybrid inflation.
  BG, C. Pallis and A. Pilaftsis, JHEP **0612** (2006) 038, [arXiv:hep-ph/0605264]

Effective Potentials for Fermions & Scalars in de Sitter

- Effective potentials in curved spacetime are generalizations of the Coleman Weinberg potential.
- Additional corrections of order H^2.
- Calculable by using position space techniques.
- UV cutoff length ϱ, de Sitter invariant.
- Dirac fermion contribution:

$$V_\psi = -\frac{m^2}{2\pi^2}\frac{1}{\varrho^2} + \frac{1}{16\pi^2}\left\{ -m^4\log(\varrho^2 m^2) - 2H^2 m^2 \log(\varrho^2 m^2)\right\}$$

Candelas, Raine (1975); corrected form in BG (2006) and Miao, Woodard (2006)

- Real scalar contribution:

$$V_\phi = \frac{m_\phi^2}{8\pi^2\varrho^2} + \frac{1}{16\pi^2}\left\{\frac{1}{4}m_\phi^4\log\left(\varrho^2 m_\phi^2\right) - H^2 m_\phi^2 \log\left(\varrho^2 m_\phi^2\right)\right\}$$

Candelas, Raine (1982)

Effective Potential for Chiral Multiplets

- Within supersymmetry, one massive Dirac fermion is accompanied by four real scalars of the same mass.
- These can be constructed from two chiral multiplets.

Two-Chiral Multiplet Effective Potential

$$V_{\text{chiral}} = 4V_\phi + V_\psi = -\frac{3}{8\pi^2} H^2 m^2 \log\left(\varrho^2 m^2\right)$$

- Flat space contributions cancel, as they should.
- Non-vanishing contribution $\propto H^2$ due to the curvature.

Example

- Consider again $t\,s\,d$.
- Superpotential W contains $W \supset h_t \bar{t} t H_u^0$.
- Neglect other Yukawa couplings, $h_t \gg h_s \gg h_d$.
- Four real scalars from H_u^0 and $\tilde{t}_L$.
- One Dirac fermion $\begin{pmatrix} t_L \\ \tilde{H}_u^0 \end{pmatrix}$.
- All these particles have the mass square $|h_t \phi|^2$.

Lifting Potential

$$V_{\text{chiral}} = -\tfrac{3}{8\pi^2} H^2 |h_t \phi|^2 \log\left(\varrho^2 |h_t \phi|^2\right)$$

- ϱ needs to be fixed by renormalization condition.
- Need to check whether also the gauge coupling g mediates lifting.

Effective Potential for the Higgs Mechanism

- Need to add gauge boson A, Goldstone G and ghost η contributions. Gauge-fixing parameter ξ.

$$
\begin{aligned}
V_A &= \mathrm{tr}\left[\frac{M^2}{8\pi^2\varrho^2}(3+\xi)+\frac{1}{64\pi^2}\left(3M^4+12H^2M^2+\xi^2M^4-4H^2\xi M^2\right)\log\left(\varrho^2M^2\right)\right] , \\
V_G &= \mathrm{tr}\left[\frac{M_G^2}{8\pi^2\varrho^2}\xi+\frac{1}{64\pi^2}\left(\xi^2M_G^4-4H^2\xi M_G^2\right)\log\left(\varrho^2M_G^2\right)\right] , \\
V_\eta &= \mathrm{tr}\left[-\frac{M^2}{4\pi^2\varrho^2}\xi-\frac{1}{64\pi^2}\left(2\xi^2M^4-8H^2\xi M^2\right)\log\left(\varrho^2M^2\right)\right] .
\end{aligned}
$$

Using $\mathrm{tr}M_{\mathrm{G}}^2=\mathrm{tr}M^2$, we find the net result, which is independent of ξ:

$$
V_{\mathrm{gauge}}=V_A+V_{\mathrm{G}}+V_\eta=\mathrm{tr}\left[\frac{3M^2}{8\pi^2\varrho^2}+\frac{1}{64\pi^2}\left(3M^4+12H^2M^2\right)\log\left(\varrho^2M^2\right)\right]
$$

First derived in Landau gauge, $\xi=0$, by Allen (1982); Ishikawa (1982).

Effective Potential for the Super-Higgs Mechanism

- Within SUSY, have additional fermionic contributions from Higgsinos/Gauginos.
  $\longrightarrow$ One set of Dirac fermions with mass matrix M_ψ satisfying $\mathrm{tr}M_\psi^2 = \mathrm{tr}M^2$. Effective potential contribution V_ψ.
- And one set of real scalars with mass matrix M^2 arising from the D-terms, yielding contribution V_D.

Effective Potential for the Super-Higgs Mechanism

$$V_{\mathrm{SH}} = V_{\mathrm{gauge}} + V_D + V_\psi = 0$$

(disappointingly, up to possible corrections of order H^4)

- This completes the possible contributions to curvature-induced lifting.

Spontaneous SUSY-breaking in F-term inflation

- Superpotential

$$\kappa S X \overline{X} - \kappa S M^2 + \lambda S H_u H_d$$

  During inflation $\langle S \rangle \neq 0$.
- For definitenenss, calculate corrections due to H_u & H_d.
- In general, X and $\overline{X}$ break a GUT-symmetry and also couple to the MSSM-fields.
- Higgs Bosons and Higgsinos, squarks and quarks acquire different masses.
- To be specific, we again consider the $u\bar{d}\bar{d}$-direction.
  Assume that $\tilde{u}_R$ corresponds to the right handed stop $\tilde{t}_R$.
  Can then expand in terms of the top-quark Yukawa coupling $h = h_t$.

Effective potential for the stop

$$V^{(1)}(\tilde{u}_R) = \frac{\kappa^2\lambda^2 M^4}{8\pi^2}\left[\ln\left(\frac{\lambda^2|S|^2}{Q^2}\right) - \frac{3}{2}\right] - \frac{1}{48\pi^2}\frac{h^2\kappa^4 M^8}{\lambda^2|S|^6}|\tilde{u}_R|^2 + \frac{1}{16\pi^2}\frac{h^4\kappa^2 M^4}{\lambda^2|S|^4}|\tilde{u}_R|^4 + \frac{1}{16\pi^2}\left(\frac{h^2\kappa^2 M^4}{\lambda^2|S|^4}|\tilde{u}_R|^2\right)^2 \ln\left(\frac{h^2\kappa^2 M^4}{\lambda^4|S|^6}|\tilde{u}_R|^2\right) + \mathcal{O}(h^6|\tilde{u}_R|^6)$$

- The $\tilde{u}_R$-dependent terms are indpendent of the renormalization scale Q.
- Unique vaccuum expectation value

$$\langle\, \tilde{u}_R \,\rangle = \frac{\kappa}{\sqrt{6}\, h} M$$

- Unique mass term

$$M^2_{\tilde{u}_R} = \frac{1}{24\pi^2}\frac{h^2\,\kappa^4}{\lambda^2}M^2$$

Summary

Lifting induced by the curved background

- Mediated by Yukawa couplings.
- Typical lifting mass square term $\sim h^2H^2$, where h is the largest Yukawa coupling of the constituents of the flat direction.
- First calculation of an effective potential in curved space, which is explicitly independent of the gauge-fixing ξ.
- Within SUSY, no lifting mediated by the gauge coupling g to order H^2.
- Dependence on renormalization constant ϱ.
- Leading correction in D-term models.

Summary

Lifting in F-term hybrid inflation

- Unique minimum of the potential and mass $\sim \frac{1}{24\pi^2} h^2 M^2 \gg H^2$, where M is a GUT-scale mass.
- Independent on the renormalization scale Q.
- Dominant contribution within F-term hybrid inflation.