Single Superfield Inflationary Models

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Inflation and supergravity

Inflation

- exponential expansion of the universe
- solves the horizon, flatness, and monopole puzzles
- seeds the large scale structure of the universe
- being tested by precise cosmological observations

Supergravity

- local (gauged) supersymmetry (SUSY)
  cf. GUT, dark matter (LSP), naturalness
- automatically including gravity
- a low-energy effective theory of superstring/M-theory
- a reasonable candidate theory to describe inflation

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What this talk is about

What we have proposed

a simple alternative mechanism of cosmic inflation in supergravity

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We have reduced the necessary matter degrees of freedom by half.

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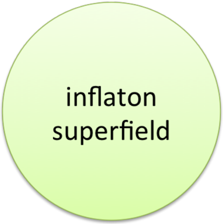

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It is a minimal framework of inflation in supergravity using a chiral superfield [Ketov and Terada, 2014b], but it is nevertheless a powerful one accommodating various inflation models.

In particular, arbitrary positive semidefinite scalar potentials can be approximately embedded in supergravity if tuning is accepted [Ketov and Terada, 2014a].

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Inflation in supergravity — some history

1983 Goncharov & Linde
first viable inflation model in SUGRA

2000 Kawasaki, Yamaguchi, & Yanagida
shift symmetry & stabilizer superfield

cf. 2010 Kallosh & Linde
generalization to arbitrary potential

2013 Ferrara, Kallosh, Linde, & Porrati
chiral & vector/linear superfield

cf. 2013 Farakos, Kehagias, & Riotto
Starobinsky model in new-minimal SUGRA

cf. 2010, 2011 Alvarez-Gaume et al.
2012 Achucarro et al.
sGoldstino inflation

2014 Ketov & Terada
various potentials with a single superfield

2015 Roest & Scalisi, & Linde
single superfield attractors

Scalar sector of 4D $\mathcal{N}=1$ supergravity

$$(-g)^{-\frac{1}{2}}\mathcal{L} = -\frac{1}{2}R - K_{i\bar{j}}D^{\mu}\bar{\phi}^{\bar{j}}D_{\mu}\phi^{i} - V, \quad (1)$$

$$V = e^{K}\left(K^{\bar{j}i}D_iW D_{\bar{j}}\bar{W} - 3|W|^2\right) + \frac{g^2}{2}H_R^{AB}D_AD_B, \quad (2)$$

where $D_iW = W_i + K_iW$.

We focus on the F-term inflationary models.

There are an exponential factor and a negative definite term.

But inflation requires a sufficiently flat and positive potential s.t.

$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 \ll 1, \qquad |\eta| = \frac{|V''|}{V} \ll 1. \quad (3)$$

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η problem

Even if we construct inflation models in global SUSY, supergravity corrections give an $\mathcal{O}(1)$ contribution to the η parameter for *e.g.* the minimal Kähler potential, $K = \bar{\phi}\phi$.

$$V = e^K V_{\text{global}} + \cdots = V_{\text{global}} + V_{\text{global}} \frac{|\phi|^2}{M_{\text{G}}^2} + \cdots, \tag{4}$$

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where $M_{\text{G}} = (8\pi G)^{-1/2} = 1$ is the reduced Planck mass.
Something like tuning or a symmetry is needed.

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Shift symmetry

$$V = e^{K}\left(K^{\bar{j}i} D_i W D_{\bar{j}} \bar{W} - 3\left|W\right|^2\right)$$

We require the Kähler potential to be invariant under the following shift transformation [Kawasaki et al., 2000],

$$\Phi \rightarrow \Phi' = \Phi - ia, \tag{6}$$

where Φ is the inflaton superfield, and a is a real transformation parameter. Then, the Kähler potential does not depend on $\mathrm{Im}\Phi$ (inflaton).

$$K(\Phi, \bar{\Phi}) = K(\Phi + \bar{\Phi}) \tag{7}$$

We break the shift symmetry by the superpotential with a small coefficient, which is determined by the normalization of CMB anisotropy. This is natural in the 't Hooft's sense ['t Hooft, 1980].

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flat but negative I

Let us take the minimal shift symmetric Kähler potential,

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The scalar potential

$$V = e^{\frac{1}{2}\left(\Phi+\bar{\Phi}\right)^2}\left(\left|W_\Phi + \left(\Phi + \bar{\Phi}\right)W\right|^2 - 3|W|^2\right) \tag{9}$$

has an approximate Z_2 symmetry under $(\Phi + \bar{\Phi}) \to -(\Phi + \bar{\Phi})$, and steep in the real direction. So, the effective potential of the inflaton in the large field region ($|W_\Phi| \ll |W|$) becomes negative,

$$V \simeq -3|W|^2 < 0. \tag{10}$$

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This problem is generic for other choices of the Kähler potential.

Strong dependence of the exponential factor on the real part leads to the extremization of the Kähler potential,

$$K_\Phi \simeq 0. \tag{11}$$

The potential becomes

$$\begin{aligned} V =& e^K \left(K^{\bar{\Phi}\Phi} |W_\Phi + K_\Phi W|^2 - 3|W|^2 \right) \\ \simeq& e^K \left(K^{\bar{\Phi}\Phi} |W_\Phi|^2 - 3|W|^2 \right) \\ \simeq& e^K \left(-3|W|^2 \right) \leq 0. \end{aligned} \tag{12}$$

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To eliminate the negative definite term, a VEV-less superfield S ($\langle S \rangle = 0$) is introduced [Kawasaki et al., 2000, Kallosh and Linde, 2010] in a way W is proportional to it,

$$W = S f(\Phi). \tag{13}$$

It is followed that

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- The form of $W = Sf(\Phi)$ is guaranteed by the R-symmetry.
- The stabilizer field S is the sGoldstino during inflation due to $V \propto |D_S W|^2$.
- Arbitrary positive semidefinite scalar potential can be approximately realized if we further impose Z_2 symmetries for S and ReΦ [Kallosh and Linde, 2010, Kallosh et al., 2011]. In this case, the potential becomes

$$V = e^{K(0,0,0,0)} K^{\bar{S}S}(0,0,0,0)|f(i\text{Im}\Phi)|^2. \tag{16}$$

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stabilizer superfield III

Sometimes, S is lighter than the Hubble scale or even tachyonic at the origin with the minimal Kähler potential,
$K = \bar{S}S + K^{(\Phi)}(\Phi + \bar{\Phi})$.
This is cured by a higher dimensional term in the Kähler potential,

$$K = \bar{S}S - \zeta(\bar{S}S)^2 + K^{(\Phi)}(\Phi + \bar{\Phi}), \quad (17)$$

where ζ is a real coefficient [Lee, 2010].
We call this the stabilization term for the stabilizer superfield S.

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Motivation

Is the double-superfield mechanism the only way to realize (large field) inflation in supergravity using chiral superfield(s)?

Are there any more economical ways to embed inflationary models in supergravity?

Is it impossible to realize various inflationary potentials with a single chiral superfield? (cf. [Goncharov and Linde, 1984])

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Single-superfield models and stabilization

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The last term is most important in the large field region.

condition for the potential to be positive in the large field region

$$K^\Phi K_\Phi \geq 3 \tag{18}$$

How to satisfy it?

We employ the stabilization term similar to the previous case. The minimal example is [Ketov and Terada, 2014b]

$$K = c(\Phi + \bar{\Phi}) + \frac{1}{2}(\Phi + \bar{\Phi})^2 - \frac{\zeta}{4}(\Phi + \bar{\Phi})^4, \tag{19}$$

with $c^2 \geq 3$ and $\zeta \gtrsim \mathcal{O}(1)$.

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$$K_\Phi = c + (\Phi + \bar{\Phi}) - \zeta(\Phi + \bar{\Phi})^3 \simeq c, \quad (21)$$

$$K_{\Phi\bar{\Phi}} = 1 - 3\zeta(\Phi + \bar{\Phi})^2 \simeq 1. \quad (22)$$

The second equalities are due to $\langle \Phi + \bar{\Phi} \rangle \simeq 0$. This is because of the SUSY breaking mass squared

$$-2e^G G_{\Phi\bar{\Phi}\Phi\bar{\Phi}} G^\Phi G^{\bar{\Phi}} \simeq 12\zeta e^G G^\Phi G^{\bar{\Phi}},$$

where $G = K + \ln |W|^2$. (Φ breaks SUSY during inflation, i.e. $|G_\Phi| \neq 0$.) Moreover, the potential blows up infinitely at $|\Phi + \bar{\Phi}| \to 1/\sqrt{3\zeta} - 0$. The field space is restricted to the narrow strip $|\Phi + \bar{\Phi}| < 1/\sqrt{3\zeta}$.

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where $G = K + \ln|W|^2$. (Φ breaks SUSY during inflation, i.e. $|G_\Phi| \neq 0$.) Moreover, the potential blows up infinitely at $|\Phi+\bar{\Phi}| \to 1/\sqrt{3\zeta} - 0$. The field space is restricted to the narrow strip $|\Phi+\bar{\Phi}| < 1/\sqrt{3\zeta}$.

[minimal K] stabilization by the quartic term

$$K = c(\Phi + \bar{\Phi}) + \frac{1}{2}(\Phi + \bar{\Phi})^2 - \frac{\zeta}{4}(\Phi + \bar{\Phi})^4 \simeq 0, \tag{20}$$

$$K_\Phi = c + (\Phi + \bar{\Phi}) - \zeta(\Phi + \bar{\Phi})^3 \simeq c, \tag{21}$$

$$K_{\Phi\bar{\Phi}} = 1 - 3\zeta(\Phi + \bar{\Phi})^2 \simeq 1. \tag{22}$$

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[minimal K] quadratic model

quadratic model

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$$W = m\Phi + W_0. \quad (24)$$

$$V \simeq |m|^2 \left(\frac{1}{2}(c^2 - 3)(\chi - \chi_0)^2 + (1 + c\text{Re}\widetilde{W}_0)^2 - 3(\text{Re}\widetilde{W}_0)^2 \right),$$

where $\Phi = \frac{1}{\sqrt{2}}(\phi + i\chi)$, $\chi_0 \equiv -\sqrt{2}\text{Im}\widetilde{W}_0$, and $\widetilde{W}_0 \equiv W_0/m$.
SUSY is broken at the vacuum.

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[minimal K] Starobinsky-like model

Starobinsky-like model

$$K = c(\Phi + \bar{\Phi}) + \frac{1}{2}(\Phi + \bar{\Phi})^2 - \frac{\zeta}{4}(\Phi + \bar{\Phi})^4, \tag{25}$$

$$W = m\left(b - e^{\sqrt{2}ia\Phi}\right). \tag{26}$$

$$V \simeq |m|^2 \left(\left(c^2 - 3\right)\left(\mathrm{Re}b - e^{-a\chi}\right)^2 + \left(c\mathrm{Im}b - \sqrt{2}ae^{-a\chi}\right)^2 - 3\left(\mathrm{Im}b\right)^2 \right).$$

where $\Phi = \frac{1}{\sqrt{2}}(\phi + i\chi)$. When $c^2 \geq 3$, there is a solution of b s.t. $V \propto (1 - e^{-a\chi})^2$. Substituting it,

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[minimal K] Starobinsky-like potential

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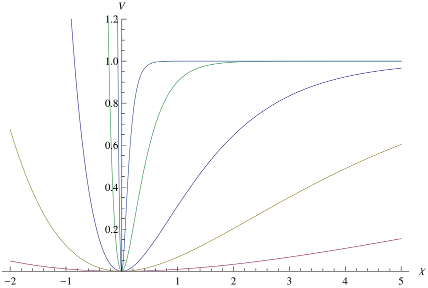

Figure: The deformed Starobinsky potential (27). The parameter a is set to $0.1, 0.3, \sqrt{2/3}$ (Starobinsky), 3, and 10 from bottom to top. The height of the potential is normalised to one. This Figure is from our paper [Ketov and Terada, 2014a].

logarithmic K

$$K = -\,a \ln\left(1 + \frac{1}{\sqrt{a}}\left(\Phi + \bar{\Phi}\right)\right) \quad \rightarrow K^{\bar{\Phi}\Phi} K_{\Phi} K_{\bar{\Phi}} = a. \tag{28}$$

If $a \geq 3$, the $|W|^2$ term does not contribute negatively to V.

$$\mathcal{L}_{\text{kin}} = -\frac{1}{\left(1 + \left(\Phi + \bar{\Phi}\right)/\sqrt{a}\right)^2}\partial_\mu \bar{\Phi}\partial^\mu \Phi, \tag{29}$$

$$V = \left(1 + \left(\Phi + \bar{\Phi}\right)/\sqrt{a}\right)^{-a} \times \left(\left(1 + \left(\Phi + \bar{\Phi}\right)/\sqrt{a}\right)^2 \left| W_\Phi - \frac{\sqrt{a}}{1 + \left(\Phi + \bar{\Phi}\right)/\sqrt{a}} W \right|^2 - 3|W|^2\right). \tag{30}$$

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For simplicity, let us stabilize the real part at the origin by the quartic term,

$$K = -a \ln \left(1 + \frac{1}{\sqrt{a}} \left(\Phi + \bar{\Phi} \right) + \frac{\zeta}{a^2} \left(\Phi + \bar{\Phi} \right)^4 \right). \tag{31}$$

The real part vanishes approximately,

$$\Phi + \bar{\Phi} \simeq 0. \tag{32}$$

The potential for the imaginary part is

$$V = |W_\Phi|^2 - \sqrt{a} \left(\bar{W} W_\Phi + W \bar{W}_{\bar{\Phi}} \right) + (a-3)|W|^2. \tag{33}$$

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- $$K = -3\ln\left(1 - \frac{1}{3}\bar{\Phi}\Phi\right). \tag{34}$$

  After canonical normalization, the potential becomes exponentially steep.

- $$K = -3\ln\left(1 - \frac{1}{6}\left(\Phi + \bar{\Phi}\right)^2\right). \tag{35}$$

  The combination $K^{\bar{\Phi}\Phi}K_\Phi K_{\bar{\Phi}} = \frac{\left(\Phi+\bar{\Phi}\right)^2}{1+\left(\Phi+\bar{\Phi}\right)^2/6}$ can not exceed 3 as long as the sign of the kinetic term of gravity is canonical.

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[logarithmic K] The case of $a = 4$

quadratic model

$$K = -4\ln\left(1 + \frac{1}{2}\left(\Phi + \bar{\Phi}\right) + \frac{\zeta}{4}\left(\Phi + \bar{\Phi}\right)^4\right), \tag{36}$$

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$$V = \frac{m^2}{2}\left(\chi - \chi_0\right)^2 + m^2 - 4m\mathrm{Re}W_0 + \left(\mathrm{Re}W_0\right)^2, \tag{38}$$

where $\chi_0 = -\sqrt{2}(\mathrm{Im}W_0)/m$. Tuning the parameters so that they satisfy $\mathrm{Re}W_0 = (2 \pm \sqrt{3})m$, the cosmological constant vanishes.

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[logarithmic K] Real part as an inflaton

It is also possible to use the real part as an inflaton by taking a different quartic term.

Starobinsky model

$$K = -3\ln\left(\left(\Phi+\bar{\Phi}\right)+\zeta\left(i\left(\bar{\Phi}-\Phi\right)-2\Phi_0\right)^4\right), \tag{39}$$

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Setting $\mathrm{Im}\Phi = \Phi_0$, the potential for the canonically normalized real part $\tilde{\phi} = \sqrt{3/2}\ln\sqrt{2}\mathrm{Re}\Phi$ is

$$V = \frac{3}{4}m^2\left(1-be^{-\sqrt{2/3}\tilde{\phi}}\right)^2, \tag{41}$$

with

$$m^2 \equiv -2\mathrm{Re}\left(c_3\bar{c}_0\right), \qquad b \equiv \frac{\mathrm{Im}\left(c_3\bar{c}_0\right)}{\mathrm{Re}\left(c_3\bar{c}_0\right)}\Phi_0. \tag{42}$$

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phase alignment condition

models of arbitrary positive semidefinite potential

$$K = -3\ln\left(1 + \frac{1}{\sqrt{3}}(\Phi + \bar{\Phi}) + \frac{\zeta}{9}(\Phi + \bar{\Phi})^4\right), \quad (43)$$

$$W(\Phi) = \frac{1}{\sqrt{2}}\widetilde{W}(-\sqrt{2}i\Phi). \quad (44)$$

Setting $\text{Re}\Phi = 0$, the potential for $\chi = \sqrt{2}\text{Im}\Phi$ is [Ketov and Terada, 2014a]

$$V = \left|\widetilde{W}'(\chi)\right|^2 - \sqrt{\frac{3}{2}}i\left(\widetilde{W}(\chi)\overline{\widetilde{W}}'(-\chi) - \overline{\widetilde{W}}(-\chi)\widetilde{W}'(\chi)\right) = \left(\widetilde{W}'(\chi)\right)^2.$$

In the second equality, we have assumed the following condition,

phase alignment condition

$$\forall A, \quad \widetilde{W}(A) = \overline{\widetilde{W}}(\bar{A}). \quad (45)$$

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restoration of SUSY after inflation

$$V \simeq \left(\widetilde{W}'(\chi)\right)^2 . \tag{46}$$

Cosmological constant vanishes at extremal points of the superpotential.

Because the potential does not depend on the constant term in the superpotential, it can be ensured that SUSY is restored after inflation by tuning of the constant.

These facts are clear for the ideal case ($\zeta \to \infty$), but they actually hold for finite values of ζ.

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Examples of the (super)potential – 1. monomial

$$K = -3\ln\left(1 + \frac{1}{\sqrt{3}}(\Phi+\bar{\Phi}) + \frac{\zeta}{9}(\Phi+\bar{\Phi})^4\right),$$

$$W(\Phi) = \frac{1}{\sqrt{2}}\widetilde{W}(-\sqrt{2}i\Phi).$$

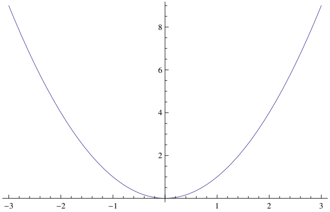
It is possible to approximately embed arbitrary positive semidefinite scalar potentials into supergravity with a single superfield.

superpotential

$$\widetilde{W}(\chi) = c_n\chi^n$$

potential

$$V = n^2|c_n|^2\chi^{2n-2}$$



Examples of the (super)potential – 2. Starobinsky-like

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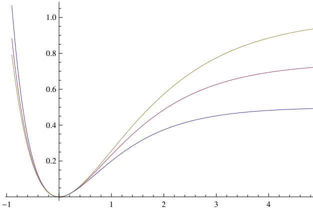
$$\widetilde{W}(\chi) = \frac{\sqrt{3\alpha}}{2}m\left(\chi + \sqrt{\frac{3\alpha}{2}}\left(e^{-\sqrt{2/3\alpha}\chi} - 1\right)\right)$$



potential

$$V = \frac{3\alpha}{4}m^2\left(1 - e^{-\sqrt{2/3\alpha}\chi}\right)^2$$

Examples of the (super)potential – 3. (double) well

$$K = -3\ln\left(1 + \frac{1}{\sqrt{3}}\left(\Phi + \bar{\Phi}\right) + \frac{\zeta}{9}\left(\Phi + \bar{\Phi}\right)^4\right),$$
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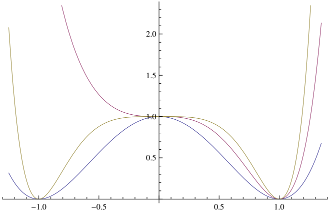
superpotential

$$\widetilde{W}(\chi) = \sqrt{\lambda}\left(\frac{1}{n+1}\chi^{n+1} - v^n\chi\right).$$

potential

$$V = \lambda\left(\chi^n - v^n\right)^2$$



Examples of the (super)potential – 4. sinusoidal

$$K = -3\ln\left(1+\frac{1}{\sqrt{3}}\left(\Phi+\bar{\Phi}\right)+\frac{\zeta}{9}\left(\Phi+\bar{\Phi}\right)^4\right),$$

$$W(\Phi) = \frac{1}{\sqrt{2}}\widetilde{W}(-\sqrt{2}i\Phi).$$

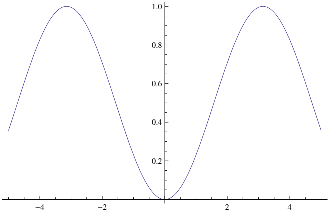
It is possible to approximately embed arbitrary positive semidefinite scalar potentials into supergravity with a single superfield.

superpotential

$$\widetilde{W}(\chi) = \frac{2\sqrt{V_0}}{n}\sqrt{1-\cos n\chi}\cot\frac{n\chi}{2}$$

potential

$$V = V_0\left(1-\cos n\chi\right)/2$$



Examples of the (super)potential – 5. polynomial chaotic

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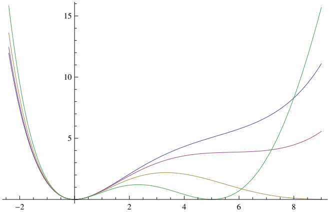
superpotential

$$\widetilde{W}(\chi) = c\chi^2\left(\frac{1}{2}-\frac{1}{3}a\chi+\frac{1}{4}b\chi^2\right)$$

potential

$$V = c^2\chi^2\left(1-a\chi+b\chi^2\right)^2$$



Examples of the (super)potential – 6. T-model

$$K = -3\ln\left(1+\frac{1}{\sqrt{3}}\left(\Phi+\bar{\Phi}\right)+\frac{\zeta}{9}\left(\Phi+\bar{\Phi}\right)^4\right),$$
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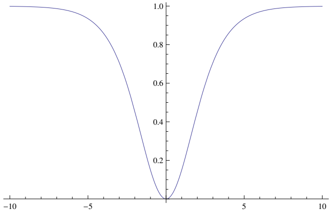
It is possible to approximately embed arbitrary positive semidefinite scalar potentials into supergravity with a single superfield.

superpotential

$$\widetilde{W}(\chi) = \sqrt{6V_0}\ln\left(\cosh\frac{\chi}{\sqrt{6}}\right)$$

potential

$$V = V_0\tanh^2\left(\frac{\chi}{\sqrt{6}}\right)$$



1. Introduction
   - Difficulties of inflation in supergravity
   - Shift symmetry and a stabilizer superfield
2. Inflation in supergravity with a single chiral superfield
   - Basic strategy and implementations
   - Embedding arbitrary scalar potentials
3. Conclusion
   - conclusion

Conclusion

- We proposed a large class of single superfield models of inflation which can realize various large as well as small field inflationary models.
- We reduced the number of d.o.f. required for large field inflation in supergravity without tuning.
- Once tuning is allowed, arbitrary positive semidefinite scalar potentials can be embedded approximately.
- These have a great impact on inflationary physics in supergravity.
- Cosmological consequences are to be further explored in future.

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