A microscopic model for inflation from supersymmetry breaking

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Contents

Motivations

- Models that relate three scales

  Supersymmetry - inflation - cosmological constant

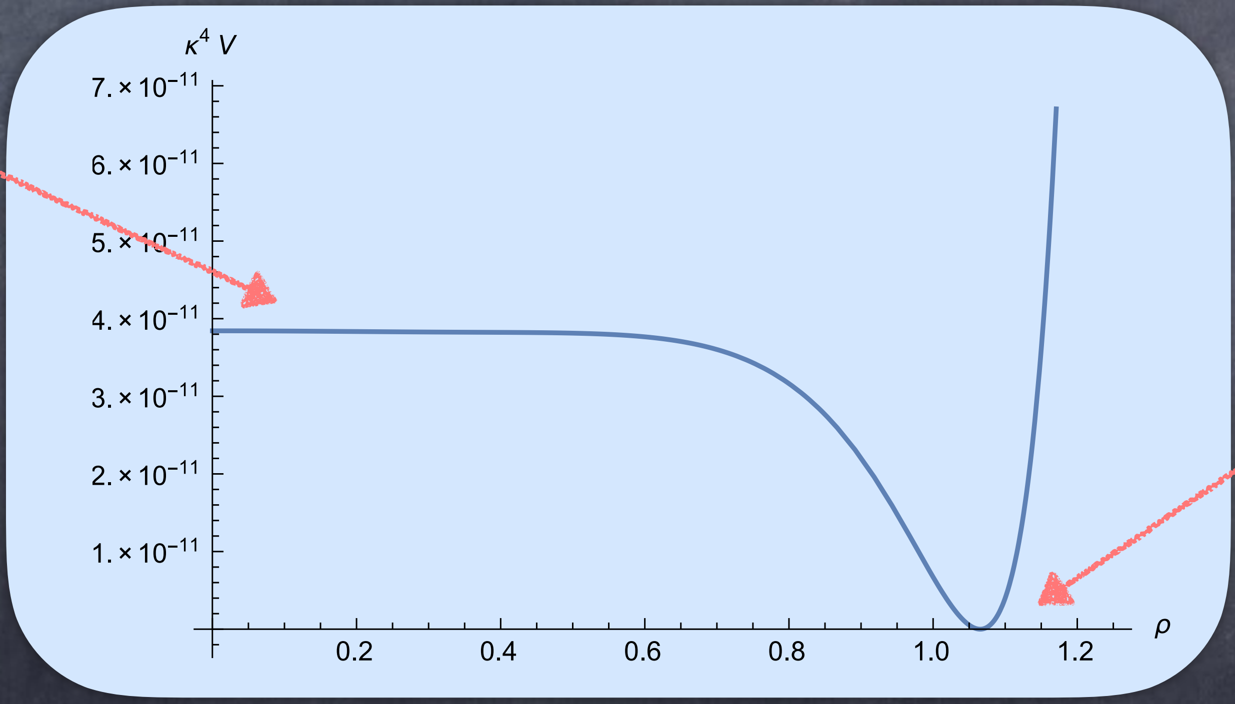
- In this talk, we will consider models in which the inflaton and the goldstino are in the same multiplet [Alvarez-Gaumé , Gomez , Jimenez, (2010,2011)]

SUSY spontaneously broken

$\langle \delta\chi \rangle \sim \langle F \rangle \sim \langle D_\phi W \rangle \neq 0$

for $\Phi = (\phi, \chi, F)$

ϕ sgoldstino = inflaton



inflaton potential with

small tuneable

cosmological constant

- We look for a UV model which gives such models as low energy effective theories, as a step toward a fundamental theory for inflation.

Inflation in supergravity : tips

consider d=4 N=1 supergravity with one chiral multiplet $\Phi = (\phi, \chi, F)$

- an action is specified in general by

Kahler potential	$K(\Phi, \bar{\Phi})$	
superpotential	$W(\Phi)$	
gauge kinetic function	$\mathcal{F}(\Phi)$	(if an internal U(1) is gauged)

- the scalar potential for ϕ in the chiral multiplet

(F-term potential)

$$V_F(\phi) = e^K (g^{\phi\bar{\phi}} |D_\phi W|^2 - 3|W|^2)$$

$$D_\phi W = W_\phi + K_\phi W$$
$$g^{\phi\bar{\phi}} = (K_{\phi\bar{\phi}})^{-1}$$

$\exists$ a gauged internal symmetry $\longrightarrow$ another contribution (D-term potential)

Inflation in supergravity : problems

1) η-problem

consider a canonical Kahler potential: $K = \bar{\Phi}\Phi$

$$\eta_V = \frac{V''}{V} = K_{\phi\bar{\phi}} + \cdots = 1 + \cdots$$

violating SR condition

2) trans-Planckian initial condition

Starobinsky type : trans-Planckian inflation

It may break validity of effective field theory

3) ϕ is complex : inflaton is one of the two real degrees of freedom

What's the fate of its companion?

others : moduli stabilisation, de Sitter vacuum, …

We propose models avoiding 1) 2) 3).

Inflation from SUSY breaking

1) consider a model $K = \bar{\Phi}\Phi + \cdots, \quad W = f\Phi \qquad \Phi = (\phi, \chi, F)$

linear superpotential breaks SUSY $\quad \langle D_\phi W \rangle = f + \cdots > 0$

goldstino : χ ⟶ ϕ as sgoldstino

inflation and SUSY breaking by a single multiplet

scalar potential:
$$\begin{aligned} V_F(\phi) &= e^K (g^{\phi\bar{\phi}} |D_\phi W|^2 - 3|W|^2) \\ &= e^{|\phi|^2}(1 - |\phi|^2 + |\phi|^4) \\ &= (1-1)|\phi|^2 + \mathcal{O}(|\phi|^4) \end{aligned}$$

η is almost zero around the origin

↓

let the inflaton start rolling around the origin

Inflation from SUSY breaking

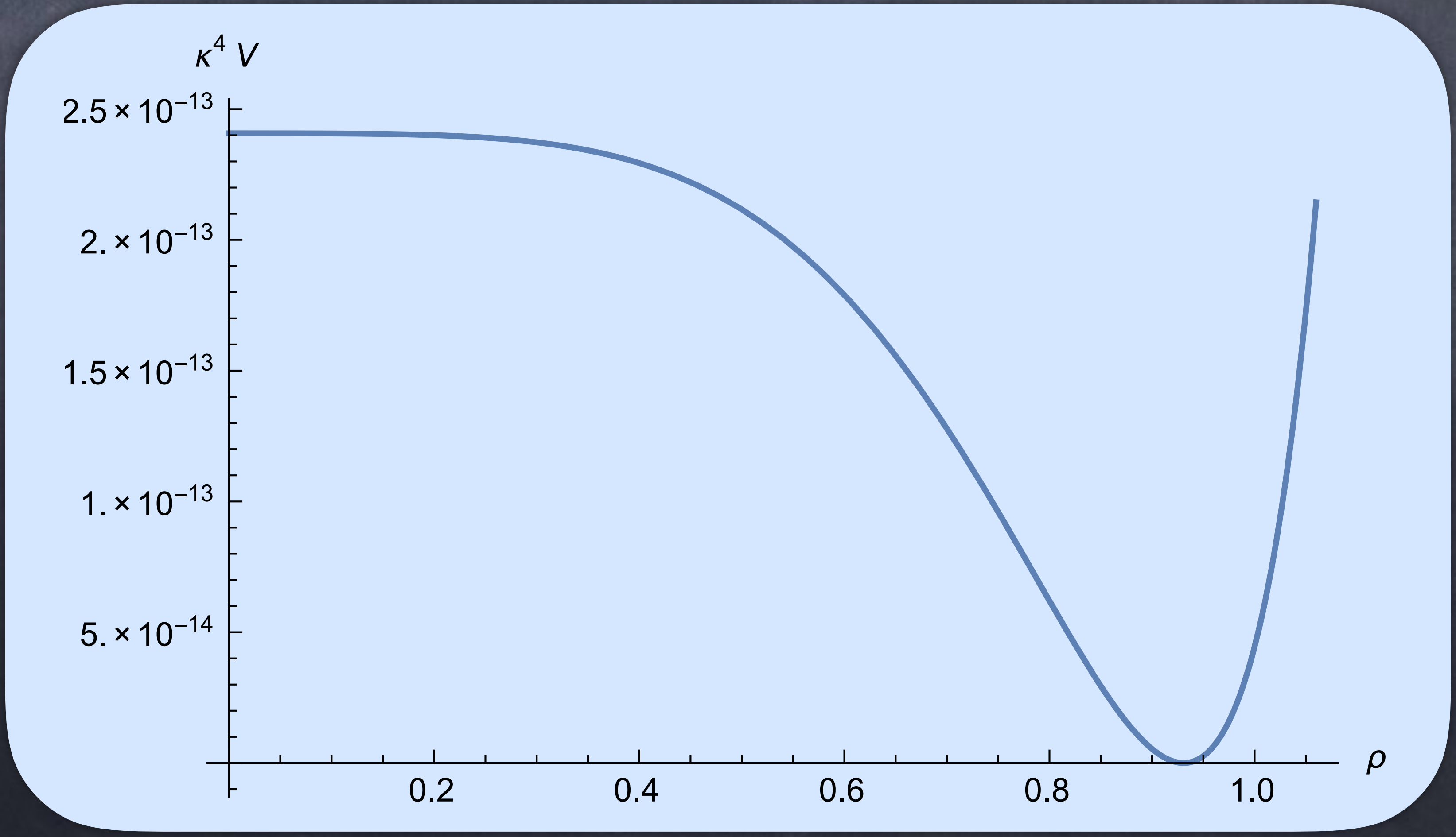
2) η is small around the origin

↓

let inflation start around the origin

↓

small field inflation



Inflation from SUSY breaking

3) inflaton is one of the two real degrees of freedom of ϕ

introduce a gauged U(1) invariance $\Phi \mapsto e^{-iq\theta}\Phi$

inflation occurs near but away from the origin

$\longrightarrow$ the phase of ϕ gets absorbed (Brout-Englert-Higgs)

$W = f\Phi$ is NOT invariant under the gauged U(1)

- U(1) = a gauged R-transformation

Inflation from SUSY breaking

3) a gauged U(1) invariance $\Phi \mapsto e^{-iq\theta}\Phi$

bonus : $\boxed{\text{D-term scalar potential} \quad V_D = \frac{1}{2}\mathscr{D}^2}$

$$\mathscr{D} = qXK_X + 1 = q|\phi|^2 + 1$$

D-term potential : positive definite

F-term potential : with a negative term $-3f^2e^K|\phi|^2$

$\longrightarrow$ global minimum by tuning them

- cannot be big near the origin : due to +ve contribution to η

  bigger contribution away from the origin is welcome.

Inflation from SUSY breaking

Near the origin: $K = \bar{X}X + A(\bar{X}X)^2 + \cdots$ $\qquad W = fX$

potential : $V = V_D + V_F$

$$V_D = \frac{q^2}{2}\left(1 + \rho^2 + 2A\rho^4\right)^2$$

$$V_F = f^2 e^{\rho^2 + A\rho^4}\left(\frac{(1 + \rho^2 + 2A\rho^4)^2}{1 + 4A\rho^2} - 3\rho^2\right)$$

slow-roll parameters (near the origin)

$$\eta = \frac{V''}{V} = 2\left(\frac{x^2 - 4A}{x^2 + 2}\right) + O(\rho^2) \qquad \left(x = \frac{q}{f}\right)$$

$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 = \eta^2\rho^2 + O(\rho^4)$$

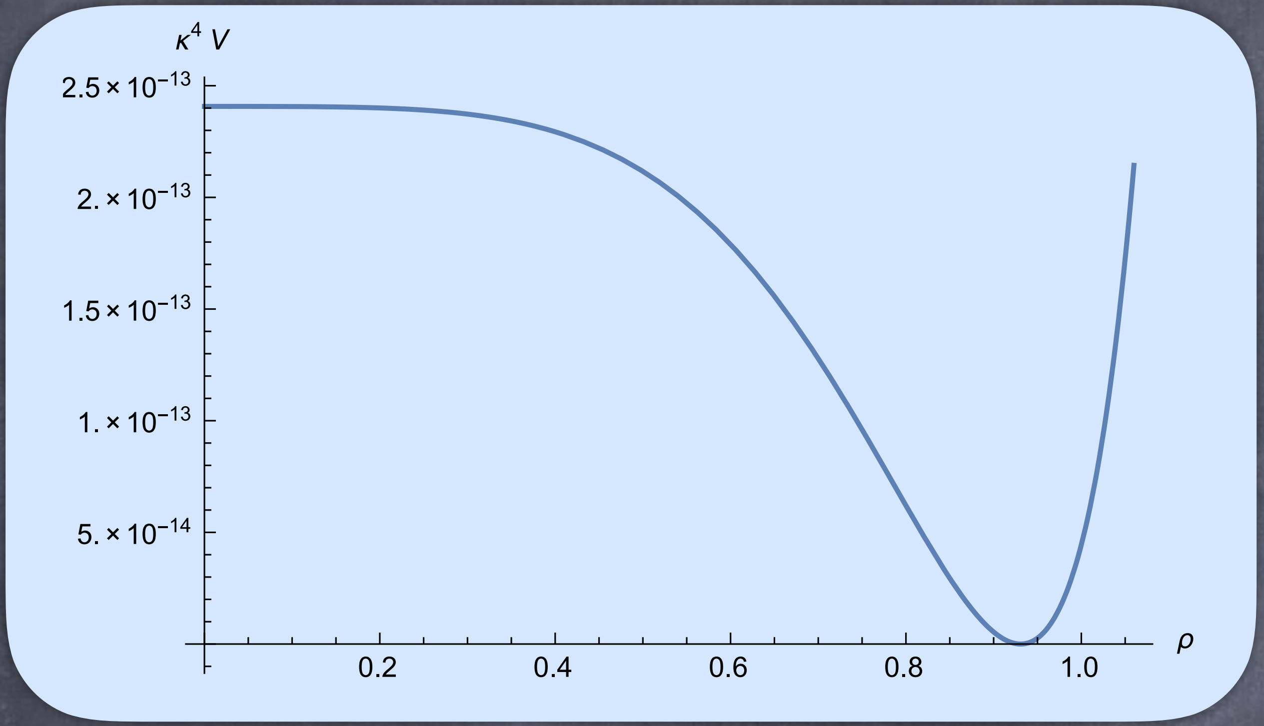
For F-term dominant: $x \ll 1 \longrightarrow \eta \simeq -4A + O(\rho^2)$

- η very small & having minimum at the origin require: $0 < A \ll 0.25$
- to satisfy CMB observation data: $\eta \sim -0.02 \Rightarrow A \sim 0.005$

example 1: $K(X,\bar{X}) = \bar{X}X + A(\bar{X}X)^2 + c\bar{X}Xe^{B\bar{X}X}$

(1706.04133) $W = fX$

correction term



$(\rho = |X|)$

Question: Can we derive them as an effective theory from a UV model?

——- no idea???

example 2: $$K(X,\bar{X}) = \bar{X}e^{xqV}X + v^2 e^{-qV} + (x-1)qV$$

(1905.00706)

$$W = fX$$

where V satisfies $$\bar{X}X = \frac{e^{-xqV}}{x}\left(v^2 e^{-qV} - x + 1 + \frac{\Delta}{1-\frac{1}{6}q\Delta V}\right)$$

- to express the Kahler potential solely in the inflaton,
  solve the equation for V perturbatively.

$$V = V_0 + V_1 X\bar{X} + V_2(X\bar{X})^2 + V_3(X\bar{X})^3 + \cdots$$

$$\longrightarrow \quad K = v^2 + K_1\bar{X}X + K_2(\bar{X}X)^2 + \cdots$$

or in terms of the canonically normalised chiral superfield Φ

$$K = \bar{\Phi}\Phi + A|\bar{\Phi}\Phi|^2 + \cdots$$

- One can fine-tune parameters x, q, v, Δ such that $0 < A \ll 0.25$

UV model?

Just presenting such models may be too a priori

Question: Can we derive them as an effective theory from a UV model?

1) $K(X,\bar{X}) = \bar{X}X + A(\bar{X}X)^2 + c\bar{X}Xe^{B\bar{X}X}$ ——- no idea

2) $K(X,\bar{X}) = \bar{X}e^{xqV}X + v^2e^{-qV} + (x-1)qV$

—— We proposed such an UV model (1905.00706)

A generalised Fayet-Iliopoulos model

- two chiral multiplets charged under gauged U(1) : $\Phi_\pm = (\phi_\pm, \psi_\pm, F_\pm)$
- one vector multiplet for the gauged U(1) : $V = (A_m, \lambda, D)$
- under U(1) transformation:

$$\Phi_+ \mapsto e^{-iq_+\Lambda}\Phi_+ \qquad \Phi_- \mapsto e^{iq_-\Lambda}\Phi_-$$

- Kahler potential, superpotential, gauge kinetic function

$$\mathcal{K} = \bar{\Phi}_+ e^{q_+ V}\Phi_+ + \bar{\Phi}_- e^{-q_- V}\Phi_-$$

$$W = f\Phi_+\Phi_-$$

$$\mathcal{F} = 1 + b\ln\frac{\Phi_-}{M}$$

to cancel $U(1)_R$ anomaly

$$b = \frac{(q_+ - q_-)^3}{24\pi^2}$$

$q_+ = q_-$ Fayet-Iliopoulos model

$q_+ \neq q_-$ generalised Fayet-Iliopoulos model

A generalised Fayet-Iliopoulos model

Remark

$q_+ = q_-$ Fayet-Iliopoulos model

well-defined both for global and local SUSY

$q_+ \neq q_-$ generalised Fayet-Iliopoulos model

well-defined ONLY for Local SUSY
because the superpotential is not gauge invariant

but it transforms as $W = f\Phi_+\Phi_- \mapsto e^{-(q_+ - q_-)\Lambda} W$

So the SUGRA action is still invariant.

A generalised Fayet-Iliopoulos model

scalar potential $$V = V_D + V_F$$

$$V_F = m^2 e^{|\phi_+|^2 + |\phi_-|^2} \left(|\phi_+|^2 + |\phi_-|^2 - |\phi_+|^2 |\phi_-|^2 \right)$$

$$V_D = \frac{1}{4} q_-^2 \frac{(x|\phi_+|^2 - |\phi_-|^2 + x - 1)^2}{2(1 + b \ln \phi_-)}$$

FI parameter and $x = \frac{q_+}{q_-}$

We focus on the vacuum $\langle \phi_+ \rangle = 0, \quad \langle \phi_- \rangle = v \neq 0$

$U(1)_R$ and SUSY spontaneously broken

A generalised Fayet-Iliopoulos model

scalar potential

$$V = \frac{1}{4} q_-^2 \frac{(x|\phi_+|^2 - |\phi_-|^2 + x - 1)^2}{2(1 + b\ln\phi_-)} + m^2 e^{|\phi_+|^2 + |\phi_-|^2} (|\phi_+|^2 + |\phi_-|^2 - |\phi_+|^2 |\phi_-|^2)$$

$\langle\phi_+\rangle = 0, \quad \langle\phi_-\rangle = v \neq 0$ U(1)$_R$ and SUSY spontaneously broken

We can find a parameter set for which

- masses of $A_m, \phi_- \gg$ masses of ϕ_+

  roughly speaking, this condition means $m^2 \ll q_-^2 v^2$

- We integrate out the heavy supermultiplets V, Φ_- in tree level to find an effective action only with Φ_+

Integrating out

rough recipe of integrating out

1. write down the action

$$S = \frac{1}{4}\int d^4x d^4\theta\ \mathcal{E}(1 + b\ln\Phi_-)W^\alpha W_\alpha\ + m\int d^4x d^2\theta\ \mathcal{E}\Phi_+\Phi_-\ \ +\text{h.c.}$$

$$+m\int d^4x d^4\theta\ E\exp\left[-\bar{\Phi}_+ e^{q_+V}\Phi_+ - \bar{\Phi}_- e^{-q_-V}\Phi_- - \tfrac{1}{3}(q_+ - q_-)V\right]$$

2. work in the unitary gauge $\Phi_- = v \longrightarrow$ only Φ_+, V remain.

3. EoM of V $\quad -\nabla^\alpha W_\alpha + e^{-K/3}q_-(x\bar{\Phi}_+ e^{xq_-V}\Phi_+ - v^2 e^{-q_-V} + x - 1) = 0$

   discard derivatives to find the effective EoM

4. Substitute it back into the unitary gauge action

5. Identity the effective Kahler and superpotentials

Integrating out: warm up example in global SUSY

We adopt the unitary gauge: $\Phi_- = v$, the action reads

$$S = \frac{1}{4}\int d^4x\ [WW]_{\theta\theta} + \int d^4x\ mv[\Phi_+]_{\theta\theta} + \text{h.c.}$$

$$+ \int d^4x\, [\bar{\Phi}_+ e^{xq_- V}\Phi_+ + v^2 e^{-q_- V} + \xi q_- V]_{\theta\theta\bar{\theta}\bar{\theta}}$$

E.O.M. for V is

$$\frac{1}{4}\mathcal{D}\bar{\mathcal{D}}^2\mathcal{D}V + xq_-\bar{\Phi}_+ e^{xq_- V}\Phi_+ - q_- v^2 e^{-q_- V} + \xi q_- = 0.$$

Due to FI-term ξq_-, $V = 0$ is not vacuum solution but it highest component get vev.

To remove tadpole, we introduce: $V = \hat{V} + \frac{1}{2}\theta\theta\bar{\theta}\bar{\theta}\,\langle D\rangle$

E.O.M becomes

$$\frac{1}{4}\mathcal{D}\bar{\mathcal{D}}^2\mathcal{D}\hat{V} + xq_-\bar{\Phi}_+ e^{xq_- V}\Phi_+ + q_- v^2(1 - e^{-q_- V}) = 0.$$

Integrating out condition: $m^2 \ll q_-^2 v^2$ or $\Delta \ll v^2$ $\quad(\Delta = \xi - v^2)$

Integrating out: warm up example in global SUSY

This gives the relation: $\bar{\Phi}_+\Phi_+ = x^{-1}v^2 e^{-q_- V(x+1)}(1-e^{q_- V}).$

We can derive the effective Kahler potential:

$$\boxed{\mathcal{K}_{\text{eff}} = -\frac{v^2}{x} + \frac{q_-\left(v^2+\xi\right)V}{2} + \frac{v^2(x+1)e^{-q_- V}}{x},}$$

Behaviour near the origin can be explore by expand (in terms of canonically normalised superfield)

$$\mathcal{K}_{\text{eff}} = |\bar{\Phi}\Phi| + A_2|\bar{\Phi}\Phi|^2 + A_3|\bar{\Phi}\Phi|^3 + \ldots, \qquad (\Phi := \sqrt{1-x\Delta/2v^2}\;\Phi_+)$$

with

$$A_2 = -\frac{x^2\left(2v^2-\Delta(2x+1)\right)}{\left(2v^2-x\Delta\right)^2}$$

The condition for $A_2 > 0$ implies $\Delta \gtrsim v^2$ and violates the integrating out condition.

We move to supergravity !

Integrating out in SUGRA

Remark

Obviously, integrating out reshuffles the fields in a complicated fashion.
So, identifying Kahler and superpotentials becomes difficult.

Furthermore, the normalisation of the kinetic terms change.
We need SUSY covariant Weyl rescaling to control the normalisation.

Controlling the normalisation is crucial
when we compute the inflaton potential and slow-roll parameters

To overcome such intricacies, we adopted the formulation with
compensators in conformal supergravity [Butter, Kugo-Yokokura-Yoshioka],
in which such rescaling degrees of freedom are manifest in superspace.

Integrating out in SUGRA

The action in unitary gauge reads

$$S = \frac{1}{4}\int d^4x d^2\theta\ \boldsymbol{\mathcal{E}} W^\alpha W_\alpha + \kappa^{-3} mv \int d^4x d^2\theta\ \boldsymbol{\mathcal{E}} C^3 \Phi_+ + \text{h.c.}$$
$$- 3\kappa^{-2}\int d^4x d^4\theta\, E C\bar{C} e^{-\kappa^2\mathcal{K}/3},$$

with

$$\kappa^2\mathcal{K} = \bar{\Phi}_+ e^{xq_- V}\Phi_+ + v^2 e^{-q_- V} + (x-1)q_- V.$$

The E.O.M is

$$-\kappa^2\nabla^\alpha W_\alpha + C\bar{C}e^{-\kappa^2\mathcal{K}/3} q_-\left(x\bar{\Phi}_+ e^{xq_- V}\Phi_+ - v^2 e^{-q_- V} + x - 1\right) = 0.$$

After removing tadpole and neglect derivative terms, the low-energy E.O.M is

$$C\bar{C}e^{-\kappa^2\mathcal{K}/3} q_-\left(x\bar{\Phi}_+ e^{xq_- V}\Phi_+ - v^2 e^{-q_- V} + x - 1\right) - q_-\Delta \simeq 0.$$

$$(\Delta = x - 1 - v^2)$$

Integrating out in SUGRA

We find the effective Kahler potential by fixing the gauge $C = \bar{C} = e^{\kappa^2 \mathcal{K}_{\text{eff}}/6}$.
We obtain

$$\kappa^2 \mathcal{K}_{\text{eff}} = \kappa^2 \mathcal{K} + 3 \ln \left(1 - \frac{1}{6} \Delta q_- V \right), \quad \kappa^3 W_{\text{eff}} = m v \Phi_+ .$$

The E.O.M and gauge fixing give us the relation:

$$\bar{\Phi}_+ \Phi_+ = x^{-1} e^{-x q_- V} \left(v^2 e^{-q_- V} - x + 1 + \frac{\Delta}{1 - \frac{1}{6} \Delta q_- V} \right)$$

A global SUSY limit is obtain in the limit $\kappa \to 0$ and by defining:

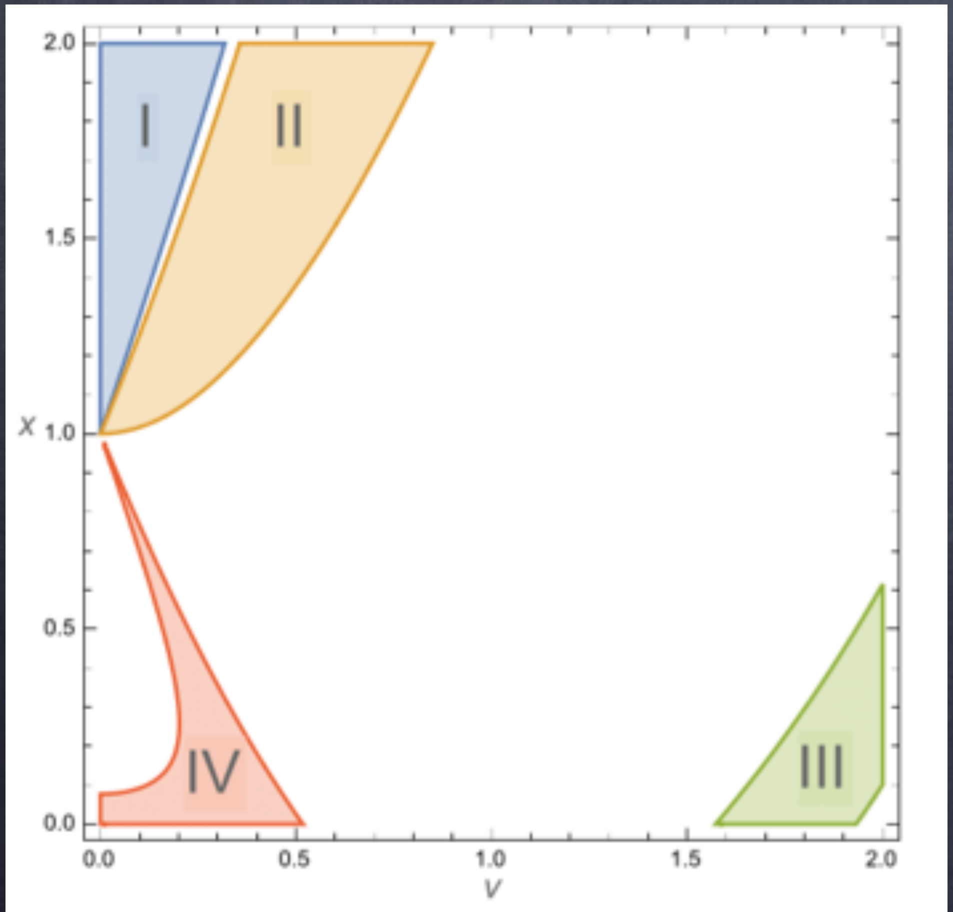
$$v^2_{\text{sugra}} = \kappa^2 v^2_{\text{susy}} , \qquad \Delta_{\text{sugra}} = \kappa^2 \Delta_{\text{susy}} .$$

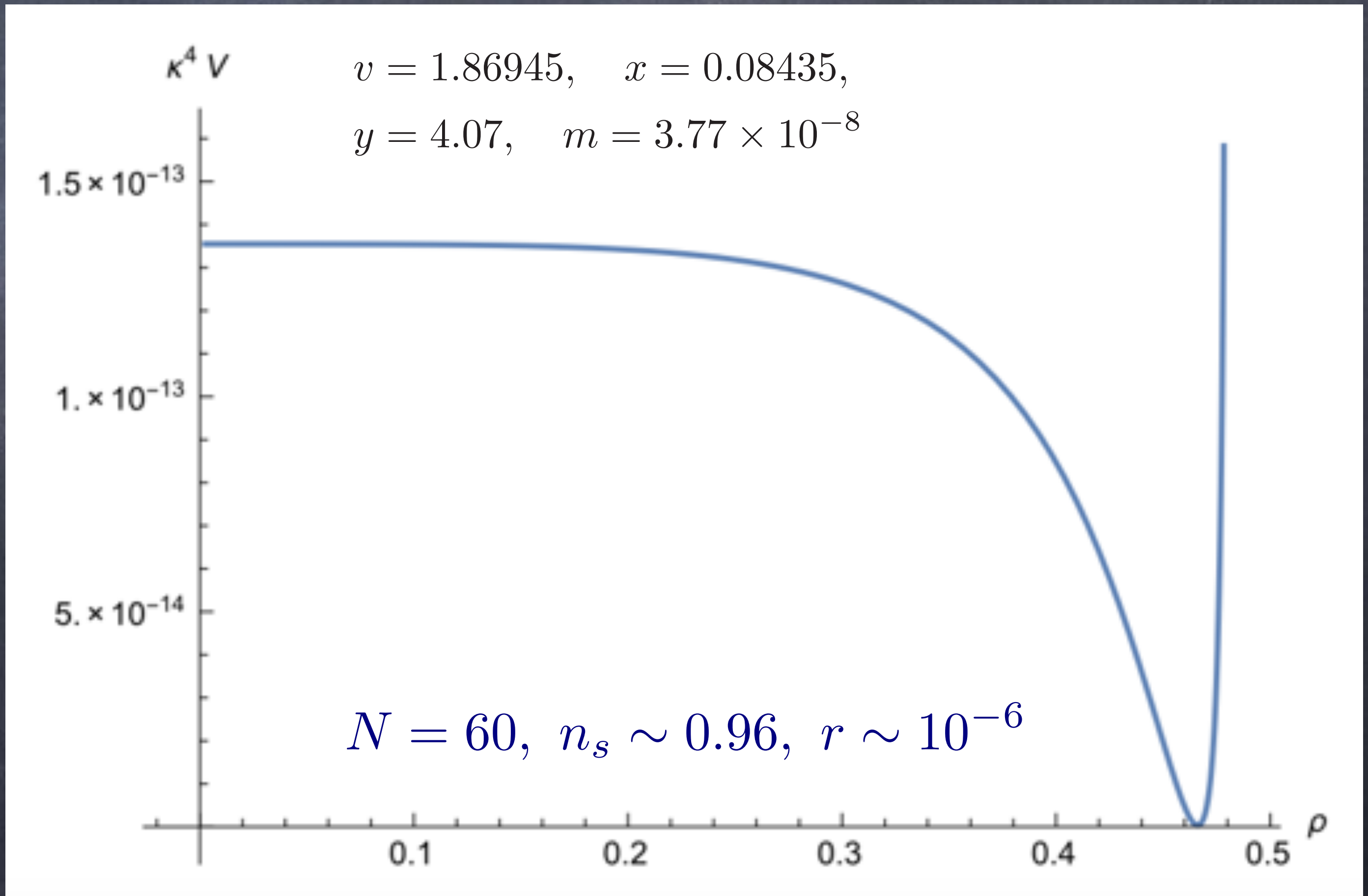
Behaviour near the origin

Behaviour near the origin can be explore (in terms of canonically normalised superfield) and in the SUGRA case we get

$$A_2 = \frac{3x^2\left(\Delta^4 + 12\Delta^3 x - 30\Delta^2 v^2 - 36\Delta v^2(2x+1) + 72v^4\right)}{2\left(\Delta^2 - 6v^2\right)\left(\Delta^2 + 3\Delta x - 6v^2\right)^2}.$$

The coloured region in which $A_2 > 0$ are divided into 4 parts. Part III is the only possible domain for slow-roll inflation with a nearby minimum with tuneable vacuum energy





Inflation from SUSY breaking revisited

Lack of $U(1)_R$ acting on Φ_+

$\downarrow$

add another $U(1)_R$ that acts ONLY on Φ_+

and is NOT broken at the vacuum $\langle \phi_+ \rangle = 0, \quad \langle \phi_- \rangle = v \neq 0$

to the microscopic model

Therefore, the UV generalised FI model has two gauged U(1) such that

$U(1)_1$	$\Phi_+ \mapsto e^{-iq_+\Lambda_1}\Phi_+$	$\Phi_- \mapsto e^{iq_-\Lambda_1}\Phi_-$
$U(1)_2$	$\Phi_+ \mapsto e^{-iQ\Lambda_2}\Phi_+$	$\Phi_- \mapsto \Phi_-$

We then found parameter sets for which the mass hierarchy justifying integrating out and the consistency with CMB data are satisfied.

Conclusion and Outlook

- We considered models in which the inflaton and the goldstino are in a single multiplet.
- For a concrete inflation in this class, we found its microscopic model model leading to the inflation as an effective theory.
- The microscopic theory is still a supergravity model, so may be far from a fundamental, unifying UV theory, if any.
- Can we realise the microscopic model from e.g. superstring?

Thank you very much!

FI term and gauged U(1) R

SUGRA $\quad -3\int d^4x d^4\theta E e^{-K/3} + \int d^4x d^2\theta \mathcal{E} W + \mathrm{h.c.}$

$P_A = P_a, Q_\alpha, \bar{Q}^{\dot{\alpha}}$

(P_A, M_{ab}) super Poincare invariant

break (D, A, K_A) by fixing $C, \bar{C}$ to 1 (+ another fixing)

conformal SUGRA

(P_A, M_{ab}, D, A, K_A) superconformally invariant

$$-3\int d^4x d^4\theta E\, C\bar{C}\, e^{-K/3} + \int d^4x d^2\theta \mathcal{E}\, C^3\, W + \mathrm{h.c.}$$

$C, \bar{C}$: chiral compensators

FI term and gauged U(1) R

conformal SUGRA

$$-3\int d^4x d^4\theta E\, C\bar{C}\, e^{-K/3} + \int d^4x d^2\theta \mathcal{E}\, C^3\, W + \mathrm{h.c.}$$

fields are characterised by charges (Δ, w) under D, A

$$D\Phi = \Delta\Phi$$

$$A\Phi = iw\Phi$$

charge assignment for invariant actions

$C : (1,2/3)$ $\bar{C} : (1, -2/3)$ matter $(0,0)$

FI term and gauged U(1) R

$$-3\int d^4xd^4\theta E\, C\bar{C}\, e^{-K/3} + \int d^4xd^2\theta\mathscr{E}\, C^3\, W + \mathrm{h.c.}$$

when invariant under SC + gauged U(1) R

chiral superfield $R\Phi = -\,iq\Phi \qquad (\Phi \mapsto e^{-iq\Lambda}\Phi)$

vector superfield $V \mapsto V + i(\Lambda - \bar{\Lambda})$

case : K,W change as $RK = 0 \qquad RW = -\,ibqW$

example : $K = \bar{\Phi}e^{qV}\Phi, \quad W = f\Phi^b$

For the action to be invariant, the compensators must also change

$$RC = \frac{1}{3}ibqC, \quad R\bar{C} = -\frac{1}{3}ibq\bar{C}$$

Inflation from SUSY breaking

3) introduce a gauged U(1) invariance $\Phi \mapsto e^{-iq\theta}\Phi$

$W = f\Phi$ is NOT invariant under the gauged U(1)

- U(1) = a gauged R-transformation : allowed in supergravity

the component action is still invariant!

$W \mapsto e^{-iq\theta}W$ is compensated by a local transformation of the fermionic coordinates $\int d^2\theta\, f\Phi$

- another reasoning : invariance under Kahler transformation

$K \mapsto K - \Lambda - \bar{\Lambda}$ $\quad W \mapsto e^{\Lambda}W$ choice of (K,W) is not unique!!

The U(1) induces a Kahler transformation