Inflation from supersymmetry breaking

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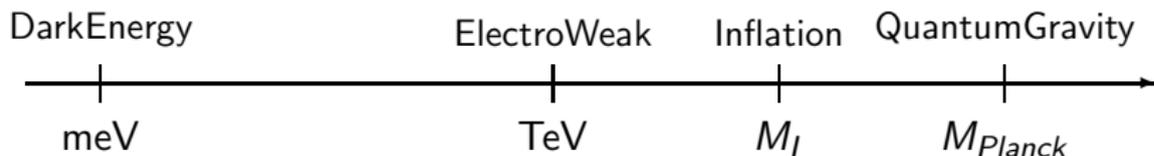
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Problem of scales

DarkEnergy   ElectroWeak   Inflation   QuantumGravity

meV   TeV M_I M_{Planck}

1. they are independent
2. possible connections
   - M_I could be near the EW scale, such as in Higgs inflation
     but large non minimal coupling to explain
   - M_{Planck} could be emergent from the EW scale
     in models of low-scale gravity and TeV strings
   → connect inflation and SUSY breaking scales
     while accommodating observed vacuum energy

Inflation in supergravity: main problems

- slow-roll conditions: the eta problem $\Rightarrow$ fine-tuning of the potential

  $$\eta = V''/V\,, \quad V_F = e^K(|DW|^2 - 3|W|^2)\,, \quad DW = W' + K'W$$

  K: Kähler potential, W: superpotential

  canonically normalised field: $K = X\bar{X} \Rightarrow \eta = 1 + \ldots$

- trans-Planckian initial conditions $\Rightarrow$ break validity of EFT

  no-scale type models that avoid the η-problem $\quad K = -3\ln(T + \bar{T})$

- stabilisation of the (pseudo) scalar companion of the inflaton

  chiral multiplets $\Rightarrow$ complex scalars

- moduli stabilisation, de Sitter vacuum, $\ldots$

Starobinsky model of inflation

$$\mathcal{L} = \frac{1}{2}R + \alpha R^2$$

Lagrange multiplier $\phi \Rightarrow \mathcal{L} = \frac{1}{2}(1+2\phi)R - \frac{1}{4\alpha}\phi^2$

Weyl rescaling $\Rightarrow$ equivalent to a scalar field with exponential potential:

$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 - \frac{M^2}{12}\left(1 - e^{-\sqrt{\frac{2}{3}}\phi}\right)^2 \qquad M^2 = \frac{3}{4\alpha}$$

Note that the two metrics are not the same

supersymmetric extension:

add D-term $\mathcal{R}\bar{\mathcal{R}}$ because F-term $\mathcal{R}^2$ does not contain R^2

$\Rightarrow$ brings two chiral multiplets

SUSY extension of Starobinsky model

$$K = -3\ln(T + \bar{T} - C\bar{C}) \quad ; \quad W = MC(T - \frac{1}{2})$$

- T contains the inflaton: $\mathrm{Re}\, T = e^{\sqrt{\frac{2}{3}}\phi}$

- $C \sim \mathcal{R}$ is unstable during inflation

  $\Rightarrow$ add higher order terms to stabilize it

  e.g. $C\bar{C} \to h(C, \bar{C}) = C\bar{C} - \zeta(C\bar{C})^2$ Kallosh-Linde '13

- SUSY is broken during inflation with C the goldstino superfield

  $\to$ model independent treatment in the decoupling sgoldstino limit

  replace C by a constrained superfield X satisfying $X^2 = 0$

  $\Rightarrow$ sgoldstino = (goldstino)^2/F

  $\Rightarrow$ minimal SUSY extension that evades stability problem

Non-linear Starobinsky supergravity

I.A.-Dudas-Ferrara-Sagnotti '14

$$K = -3\ln(T + \bar{T} - X\bar{X}) \quad ; \quad W = MXT + fX + f/3 \qquad \Rightarrow$$

$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 - \frac{M^2}{12}\left(1 - e^{-\sqrt{\frac{2}{3}}\phi}\right)^2 - \frac{1}{2}e^{-2\sqrt{\frac{2}{3}}\phi}(\partial a)^2 - \frac{M^2}{18}e^{-2\sqrt{\frac{2}{3}}\phi}a^2$$

- axion a much heavier than ϕ during inflation, decouples:

  $m_\phi = \frac{M}{3}e^{-\sqrt{\frac{2}{3}}\phi_0} << m_a = \frac{M}{3}$

- inflation scale M independent from NL-SUSY breaking scale f

  $\Rightarrow$ compatible with low energy SUSY

- however inflaton different from goldstino superpartner

- also initial conditions require trans-planckian values for ϕ $(\phi > 1)$

Inflation from supersymmetry breaking

Inflaton : goldstino superpartner in the presence of a gauged R-symmetry

- linear superpotential $W = f X \Rightarrow$ no η-problem

$$
\begin{aligned}
V_F &= e^K \left(|DW|^2 - 3|W|^2 \right) \\
&= e^K \left(|1 + K_X X|^2 - 3|X|^2 \right) |f|^2 \qquad K = X\bar{X} \\
&= e^{|X|^2} \left(1 - |X|^2 + \mathcal{O}(|X|^4) \right) |f|^2 = \mathcal{O}(|X|^4) \quad \Rightarrow \eta = 0 + \dots
\end{aligned}
$$

- inflation around a maximum of scalar potential (hill-top) $\Rightarrow$ small field

  no large field initial conditions

- gauge R-symmetry: (pseudo) scalar absorbed by the $U(1)_R$

- vacuum energy at the minimum: tuning between V_F and V_D

Two classes of models

- Case 1: R-symmetry is restored during inflation (at the maximum)
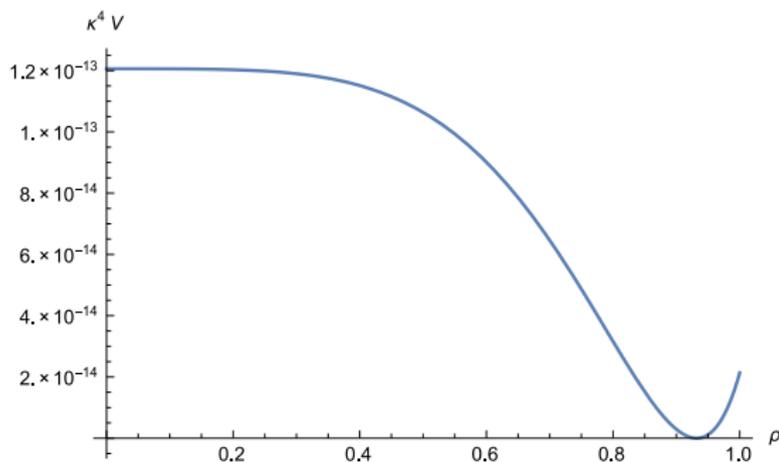
- Case 2: R-symmetry is (spontaneously) broken everywhere

  (and restored at infinity)

  example: toy model of SUSY breaking

$$\mathcal{K}(X, \bar{X}) = \kappa^{-2} X \bar{X} + \kappa^{-4} A (X \bar{X})^2 \qquad A > 0 \qquad \text{[15]}$$

$$W(X) = \kappa^{-3} f X \qquad \Rightarrow$$

$$f(X) = 1 \qquad (+\beta \ln X \text{ to cancel anomalies but } \beta \text{ very small})$$

$$\mathcal{V} = \mathcal{V}_F + \mathcal{V}_D$$

$$\mathcal{V}_F = \kappa^{-4} f^2 e^{X \bar{X}(1 + A X \bar{X})} \left[-3 X \bar{X} + \frac{\left(1 + X \bar{X}(1 + 2 A X \bar{X})\right)^2}{1 + 4 A X \bar{X}} \right]$$

$$\mathcal{V}_D = \kappa^{-4} \frac{q^2}{2} \left[1 + X \bar{X}(1 + 2 A X \bar{X}) \right]^2 \qquad \text{[12]}$$

Assume inflation happens around the maximum $|X| \equiv \rho \simeq 0 \qquad \Rightarrow$

Case 1: predictions

slow-roll parameters

$$\eta = \frac{1}{\kappa^2}\left(\frac{V''}{V}\right) = 2\left(\frac{-4A + x^2}{2 + x^2}\right) + \mathcal{O}(\rho^2) \qquad x = q/f \quad [12]$$

$$\epsilon = \frac{1}{2\kappa^2}\left(\frac{V'}{V}\right)^2 = 4\left(\frac{-4A + x^2}{2 + x^2}\right)^2 \rho^2 + \mathcal{O}(\rho^4) \simeq \eta^2 \rho^2$$

η small: for instance $x \ll 1$ and $A \sim \mathcal{O}(10^{-1})$

inflation starts with an initial condition for $\phi = \phi_*$ near the maximum

and ends when $|\eta| = 1$

$\Rightarrow$ number of e-folds $N = \int_{end}^{start} \frac{V}{V'} = \kappa \int \frac{1}{\sqrt{2\epsilon}} \simeq \frac{1}{|\eta_*|}\ln\left(\frac{\rho_{\text{end}}}{\rho_*}\right)$ [17]

Case 1: predictions

$$\text{amplitude of density perturbations} \quad A_s = \frac{\kappa^4 V_*}{24\pi^2 \epsilon_*} = \frac{\kappa^2 H_*^2}{8\pi^2 \epsilon_*}$$

$$\text{spectral index} \quad n_s = 1 + 2\eta_* - 6\epsilon_* \simeq 1 + 2\eta_*$$

$$\text{tensor} - \text{to} - \text{scalar ratio} \quad r = 16\epsilon_*$$

Planck '15 data : $\eta \simeq -0.02$, $A_s \simeq 2.2 \times 10^{-9}$, $N \gtrsim 50$

$$\Rightarrow r \lesssim 10^{-4}, \ H_* \lesssim 10^{12} \text{ GeV} \qquad \text{assuming } \rho_{\text{end}} \lesssim 1/2$$

Question: can a 'nearby' minimum exist with a tiny +ve vacuum energy?

Answer: Yes in a 'weaker' sense: perturbative expansion [9]

valid for the Kähler potential but not for the slow-roll parameters

generic V (not fine-tuned) $\Rightarrow 10^{-9} \lesssim r \lesssim 10^{-4}$, $10^{10} \lesssim H_* \lesssim 10^{12}$ GeV

Fayet-Iliopoulos (FI) D-terms in supergravity

D-term contribution: positive contribution to η $\Rightarrow$ should stay small [10]

its role: not important for inflation

- $U(1)$ absorbs the pseudoscalar partner of inflaton
- allows tuning the EW vacuum energy at a tiny positive value in case 2

Question: is it possible to have inflation by SUSY breaking via D-term?

the inflaton should belong to a massive vector multiplet as before

FI-term in supergravity very restrictive:

constant FI term exists only by gauging the R-symmetry [9]

A new FI term was written recently Cribiori-Farakos-Tournoy-Van Proeyen '18

gauge invariant at the Lagrangian level but non-local

becomes local and very simple in the unitary gauge

A new FI term

Global supersymmetry:

gauge field-srength superfield

$$\mathcal{L}_{\mathrm{FI}}^{new} = \xi_1 \int d^4\theta \frac{\mathcal{W}^2 \overline{\mathcal{W}}^2}{\mathcal{D}^2 \mathcal{W}^2 \bar{\mathcal{D}}^2 \overline{\mathcal{W}}^2} \mathcal{D}\mathcal{W} = -\xi_1 \mathrm{D} + \text{fermions}$$

It makes sense only when $< \mathrm{D} > \neq 0 \Rightarrow$ SUSY broken by a D-term

Supergravity generalisation: straightforward

unitary gauge: goldstino = $U(1)$ gaugino = $0 \Rightarrow$ standard sugra $-\xi_1 \mathrm{D}$

Pure sugra + one vector multiplet $\Rightarrow$ [19]

$$\mathcal{L} = R + \bar{\psi}_\mu \sigma^{\mu\nu\rho} D_\rho \psi_\nu + m_{3/2} \bar{\psi}_\mu \sigma^{\mu\nu} \psi_\nu - \frac{1}{4} F_{\mu\nu}^2 - \left(-3m_{3/2}^2 + \frac{1}{2}\xi_1^2 \right)$$

- $\xi_1 = 0 \Rightarrow$ AdS supergravity

- $\xi_1 \neq 0$ uplifts the vacuum energy and breaks SUSY

  e.g. $\xi_1 = \sqrt{6}m_{3/2} \Rightarrow$ massive gravitino in flat space

New FI term with matter

net result: $\xi_1 \rightarrow \xi_1 \, e^{K/3}$

- Not invariant under Kähler transformations

  $K(X, \bar{X}) \rightarrow K + J(X) + \bar{J}(\bar{X})$ $W \rightarrow e^{-J} W$

- $U(1)$ cannot be an R-symmetry

however R-symmetry becomes ordinary $U(1)$ by a Kähler transformation:

$J = \ln(W/W_0) \Rightarrow W \rightarrow W_0$ constant and $K \rightarrow K + \ln|W/W_0|^2$

The new and standard FI terms can co-exist in this basis

<div align="right">I.A.-Chatrabhuti-Isono-Knoops '18</div>

Case 1 model for $A = 0$ and $W = f \, X^b$ $(W_0 = f, \kappa = 1) \Rightarrow$ [9]

Model of inflation on D-terms

$K = X\bar{X} + b \ln X\bar{X}$; $W = f$ (*b*: standard FI constant) $\Rightarrow$

$$\mathcal{V}_F = f^2 e^{\rho^2} \left[\rho^{2(b-1)} (b + \rho^2)^2 - 3\rho^{2b} \right]$$

$$\mathcal{V}_D = \frac{q^2}{2} \left(\rho^2 + b + \xi \rho^{\frac{4b}{3}} e^{\frac{1}{3}\rho^2} \right)^2 \quad \xi = \xi_1 / q$$
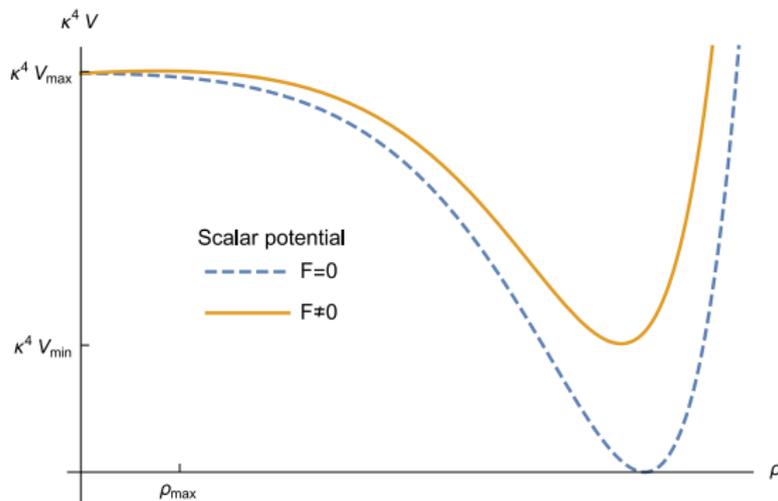
<u>Case $f = 0$</u> (pure D-term potential):

maximum at $\rho = 0 \Rightarrow b = 3/2$ and $\xi \leq -1$ (or $b = 0$ and $-2/3 \leq \xi \leq 0$)

$$\mathcal{V}_D = \frac{q^2}{2} \left[b + \rho^2 \left(1 + \xi e^{\frac{1}{3}\rho^2} \right) \right]^2$$

- $\xi = -1$: effective charge of X vanishes
- supersymmetric minimum at D=0

Pure D-term potential

Case $f \neq 0$:

- maximum is shifted at $\rho = -\frac{3f^2}{4(1+\xi)q^2}$
- minimum is lifted up and SUSY is broken by both D and F of $\mathcal{O}(f)$

Predictions for inflation

slow-roll parameters

$$\eta = \frac{4(1+\xi)}{3} + \mathcal{O}(\rho^2)$$

$$\epsilon = \frac{16}{9}(1+\xi)^2\rho^2 + \mathcal{O}(\rho^4) \simeq \eta^2\rho^2$$

$$N \sim \frac{1}{|\eta_*|}\ln\left(\frac{\rho_{\text{end}}}{\rho_*}\right)$$

$\Rightarrow$ same main results as before (F-term dominated inflation) !! [10]

However allowing higher order correction to the Kähler potential

one can obtain r as large as 0.015 (near the experimental bound) [20]

The cosmological constant in Supergravity

Highly constrained: $\Lambda \geq -3m_{3/2}^2$

- equality $\Rightarrow$ AdS (Anti de Sitter) supergravity

  $m_{3/2} = W_0$: constant superpotential

- inequality: dynamically by minimising the scalar potential

  $\Rightarrow$ uplifting Λ and breaking supersymmetry

Λ is not an independent parameter for arbitrary breaking scale $m_{3/2}$

What about breaking SUSY with a $<D>$ triggered by a constant FI-term?

Standard supergravity: possible only for a gauged $U(1)_R$ symmetry:

- absence of matter $\Rightarrow W_0 = 0 \rightarrow$ dS vacuum   Friedman '77

- presence of charged matter $\Rightarrow$ also F-term VEV (as above)

Exception: non-linear supersymmetry

New FI-term evades this problem in the absence of matter [13]

Presence of matter $\Rightarrow$ non trivial scalar potential

but breaks Kähler invariance

Also this term is not unique: one can in principle introduce new function

Question: can one modify this term to respect Kähler invariance

in the presence of matter?

Answer: yes, constant FI-term + fermions as in the absence of matter

$\Rightarrow$ constant uplift of the potential, Λ free (+ve) parameter besides $m_{3/2}$

Conclusions

Challenge of scales: at least three very different (besides M_{Planck})

electroweak, dark energy, inflation, SUSY?

their origins may be connected or independent

General class of models with inflation from SUSY breaking:

identify inflaton with goldstino superpartner

- (gauged) R-symmetry restored (case 1)

  or broken (case 2) during inflation

  small field, avoids the η-problem, no (pseudo) scalar companion

- D-term inflation is also possible using a new FI term