Inflation from supersymmetry breaking

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Problem of scales

- describe high energy (SUSY?) extension of the Standard Model

  unification of all fundamental interactions

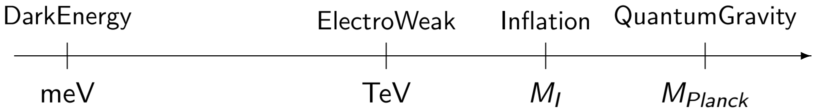
- incorporate Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant

- describe possible accelerated expanding phase of our universe

  models of inflation (approximate de Sitter)

$\Rightarrow$ 3 very different scales besides M_{Planck} : [4]



Relativistic dark energy 70-75% of the observable universe

negative pressure: $p = -\rho \Rightarrow$ cosmological constant

$$R_{ab} - \frac{1}{2} R g_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab} \Rightarrow \rho_\Lambda = \frac{c^4 \Lambda}{8\pi G} = -p_\Lambda$$

Two length scales:

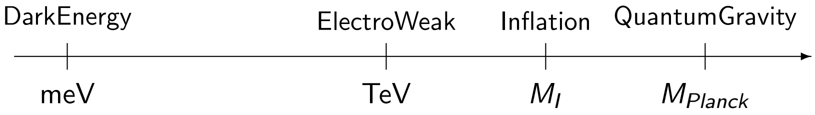
- $[\Lambda] = L^{-2} \leftarrow$ size of the observable Universe

  $\Lambda_{obs} \simeq 0.74 \times 3H_0^2/c^2 \simeq 1.4 \times (10^{26}\,\mathrm{m})^{-2}$

  ↖ Hubble parameter $\simeq 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

- $[\frac{\Lambda}{G} \times \frac{c^3}{\hbar}] = L^{-4} \leftarrow$ dark energy length $\simeq 85\mu\mathrm{m}$

Problem of scales



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, ...

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

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

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

- 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

I.A.-Chatrabhuti-Isono-Knoops '16, '17

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

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

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

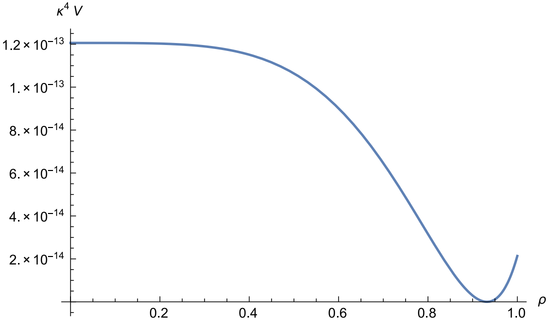
- inflation around a maximum of scalar potential (hill-top) $\Rightarrow$ small field

  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

Case 1: R-symmetry restored during inflation [13]

$$\mathcal{K}(X,\bar{X}) = \kappa^{-2}X\bar{X} + \kappa^{-4}A\,(X\bar{X})^2 \qquad A > 0 \qquad \text{[17]}$$

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

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

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

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

$$\mathcal{V}_D = \kappa^{-4}\frac{q^2}{2}\left[1+X\bar{X}(1+2AX\bar{X})\right]^2 \qquad \text{[14]}$$

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

Case 1: predictions

slow-roll parameters

$$\eta = \frac{1}{\kappa^2}\left(\frac{V''}{V}\right) = 2\left(\frac{-4A+x^2}{2+x^2}\right) + \mathcal{O}(\rho^2) \qquad x = q/f \quad [14]$$

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

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 $N = \int_{end}^{start} \frac{V}{V'} = \kappa \int \frac{1}{\sqrt{2\epsilon}} \simeq \frac{1}{|\eta_*|} \ln\left(\frac{\rho_{\rm end}}{\rho_*}\right)$ [19]

Case 1: predictions

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

spectral index $n_s = 1 + 2\eta_* - 6\epsilon_* \simeq 1 + 2\eta_*$

tensor – to – scalar ratio $r = 16\epsilon_*$

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

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

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

Answer: Yes in a 'weaker' sense: perturbative expansion [11]

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 $\eta \Rrightarrow$ should stay small [12]

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 [11]

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

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

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

Supergravity generalisation: straightforward

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

Pure sugra $+$ one vector multiplet $\Rightarrow$

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

- $\xi_1 = 0 \Rightarrow$ 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: $\xi_1 \to \xi_1 \, e^{2K/3}$

- Not invariant under Kähler transformations

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

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

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

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

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

I.A.-Chatrabhuti-Isono-Knoops '18

Case 1 model for $A = 0$ and $W = f\, X^b$ $(W_0 = f, \kappa = 1) \Rightarrow$ [11]

Model of inflation on D-terms

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

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

$$\mathcal{V}_D = \frac{q^2}{2}\left(\rho^2 + b + \xi\rho^{\frac{4b}{3}} e^{\frac{2}{3}\rho^2}\right)^2 \quad \xi = \xi_1/q$$

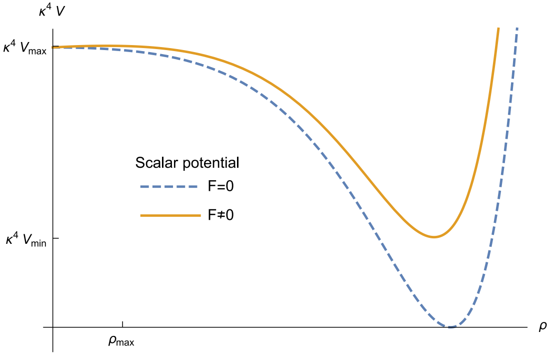
Case $f = 0$ (pure D-term potential):

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

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

- $\xi = -1$: 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

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

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

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

$\Rightarrow$ same main results as before (F-term dominated inflation) !! [12]

However allowing higher order correction to the Kähler potential

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

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