Inflation from supersymmetry breaking

I. Antoniadis

Albert Einstein Center, University of Bern
and
LPTHE, Sorbonne Université, CNRS Paris

What Comes Beyond the Standard Models?

24-30 June 2018, Bled, Slovenia

Problem of scales

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

  unification of all fundamental interactions

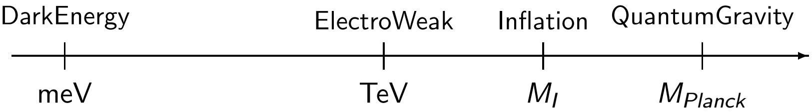
- incorporate Dark Energy

  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:

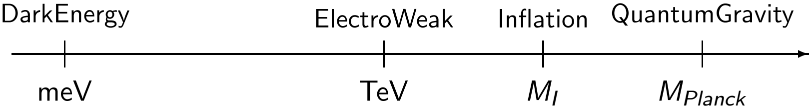
- $[\Lambda] = L^{-2} \leftarrow$ size of the observable Universe

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

  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
   - $\rightarrow$ 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 [11]

Non-linear supersymmetry $\Rightarrow$ goldstino mode χ

Volkov-Akulov '73

Effective field theory of SUSY breaking at low energies

Analog of non-linear σ-model $\Rightarrow$ constraint superfields

Rocek-Tseytlin '78, Lindstrom-Rocek '79, Komargodski-Seiberg '09

Goldstino: chiral superfield X_{NL} satisfying $X_{NL}^2 = 0 \Rightarrow$

$$X_{NL}(y) = \frac{\chi^2}{2F} + \sqrt{2}\theta\chi + \theta^2 F \qquad y^\mu = x^\mu + i\theta\sigma^\mu\bar{\theta}$$

$$= F\Theta^2 \qquad \Theta = \theta + \frac{\chi}{\sqrt{2}F}$$

$$\mathcal{L}_{NL} = \int d^4\theta X_{NL}\bar{X}_{NL} - \frac{1}{\sqrt{2}\kappa}\left\{\int d^2\theta X_{NL} + h.c.\right\} = \mathcal{L}_{Volkov-Akulov}$$

R-symmetry with $[\theta]_R = [\chi]_R = 1$ and $[X]_R = 2$ $\qquad F = \frac{1}{\sqrt{2}\kappa} + \dots$

Non-linear SUSY transformations:

$$\delta\chi_\alpha = \frac{\xi_\alpha}{\kappa} + \kappa\,\Lambda_\xi^\mu\,\partial_\mu\chi_\alpha \qquad \Lambda_\xi^\mu = -i\left(\chi\sigma^\mu\bar{\xi} - \xi\sigma^\mu\bar{\chi}\right)$$

κ: goldstino decay constant (SUSY breaking scale) $\qquad \kappa = (\sqrt{2}m_{susy})^{-2}$

Volkov-Akulov action:

Define the 'vierbein': $\quad E_\mu^a = \delta_\mu^a + \kappa^2\, t_\mu^a \qquad t_\mu^a = i\chi\overset{\leftrightarrow}{\partial}_\mu\sigma^a\bar{\chi}$

$\delta(\det E) = \kappa\,\partial_\mu\left(\Lambda_\xi^\mu\,\det E\right) \Rightarrow$ invariant action:

$$S_{VA} = -\frac{1}{2\kappa^2}\int d^4x\,\det E = -\frac{1}{2\kappa^2} - \frac{i}{2}\chi\sigma^\mu\overset{\leftrightarrow}{\partial}_\mu\bar{\chi} + \ldots$$

Non-linear SUSY in supergravity

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

$$K = -3\log(1 - X\bar{X}) \equiv 3X\bar{X} \quad ; \quad W = f\,X + W_0 \qquad X \equiv X_{NL}$$

$$\Rightarrow \quad V = \frac{1}{3}|f|^2 - 3|W_0|^2 \quad ; \quad m_{3/2}^2 = |W_0|^2$$

- V can have any sign contrary to global NL SUSY [24]
- NL SUSY in flat space $\Rightarrow f = 3\, m_{3/2} M_p$
- R-symmetry is broken by W_0
- Dual gravitational formulation: $(\mathcal{R} - 6W_0)^2 = 0$ I.A.-Markou '15

  chiral curvature superfield
- Minimal SUSY extension of R^2 gravity [7]

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

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

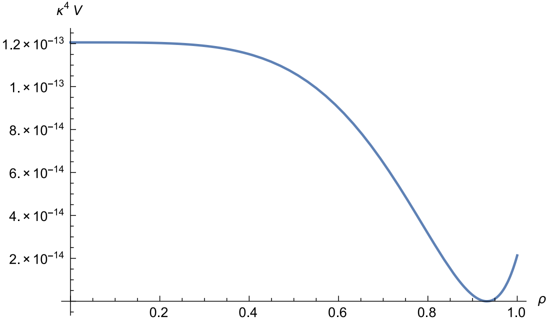
- inflation around a maximum of scalar potential (hill-top) $\Rightarrow$ small field

  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 [16]

$$\mathcal{K}(X,\bar{X}) = \kappa^{-2}X\bar{X} + \kappa^{-4}A\,(X\bar{X})^2 \qquad A > 0$$ [20]

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

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

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

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

$$\mathcal{V}_D = \kappa^{-4}\frac{q^2}{2}\left[1+X\bar{X}(1+2AX\bar{X})\right]^2$$ [17]

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

Case 1: predictions

slow-roll parameters

$$\eta = \frac{1}{\kappa^2}\left(\frac{V''}{V}\right) = 2\left(\frac{-4A+x^2}{2+x^2}\right) + \mathcal{O}(\rho^2) \qquad x = q/f \quad [17]$$

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

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 $N = \int_{end}^{start} \frac{V}{V'} = \kappa \int \frac{1}{\sqrt{2\epsilon}} \simeq \frac{1}{|\eta_*|} \ln\left(\frac{\rho_{\mathrm{end}}}{\rho_*}\right)$ [22]

Case 1: predictions

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

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

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

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

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

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

Answer: Yes in a 'weaker' sense: perturbative expansion [14]

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 $\eta \Rightarrow$ should stay small [15]

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 [14]

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

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

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

Supergravity generalisation: straightforward

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

Pure sugra + one vector multiplet $\Rightarrow$ [24]

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

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

- 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 $W = f\,X^b$ $(W_0 = f, \kappa = 1) \Rightarrow$ [14]

Model of inflation on D-terms

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

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

$$\mathcal{V}_D = \frac{q^2}{2}\left(\rho^2 + b + \xi\rho^{\frac{4b}{3}}e^{\frac{1}{3}\rho^2}\right)^2 \qquad \xi = \xi_1/q$$

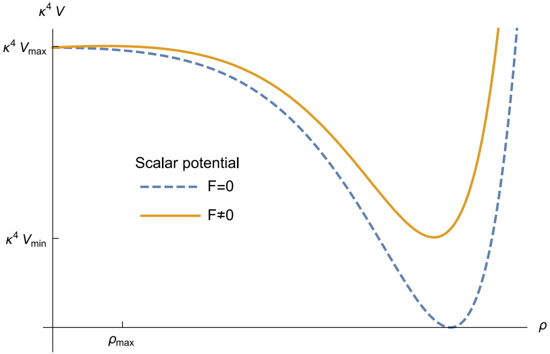
Case $f = 0$ (pure D-term potential):

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

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

- $\xi = -1$: 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

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

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

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

$\Rightarrow$ same main results as before (F-term dominated inflation) !! [15]

However allowing higher order correction to the Kähler potential

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

The cosmological constant in Supergravity

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

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 $\Rightarrow$ $W_0 = 0 \to$ dS vacuum   Friedman '77
- presence of charged matter $\Rightarrow$ also F-term VEV (as above)

The cosmological constant in Supergravity

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

Exception: non-linear supersymmetry [10]

New FI-term evades this problem in the absence of matter [18]

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