

# Inflation from supersymmetry breaking

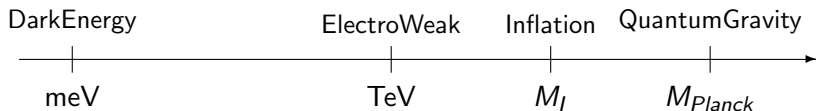
I. Antoniadis

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

String Phenomenology 2018, 2-6 July, Warsaw, Poland



# 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:  $K = X\bar{X} \Rightarrow \eta = 1 + \dots$

- trans-Planckian initial conditions  $\Rightarrow$  break validity of EFT  
no-scale type models that avoid the  $\eta$ -problem  $K = -3\ln(T + \bar{T})$
- stabilisation of the (pseudo) scalar companion of the inflaton  
chiral multiplets  $\Rightarrow$  complex scalars
- moduli stabilisation, de Sitter vacuum, ...

# Starobinsky model of inflation

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

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

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

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

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:  $\text{Re } T = e^{\sqrt{\frac{2}{3}}\phi}$
- $C \sim \mathcal{R}$  is unstable during inflation

⇒ add higher order terms to stabilize it

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

- SUSY is broken during inflation with  $C$  the goldstino superfield

→ model independent treatment in the decoupling sgoldstino limit  
replace  $C$  by a constrained superfield  $X$  satisfying  $X^2 = 0$

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

⇒ minimal SUSY extension that evades stability problem

# Non-linear Starobinsky supergravity

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

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

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

- axion  $a$  much heavier than  $\phi$  during inflation, decouples:

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

- 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  $\phi$  ( $\phi > 1$ )

# Inflation from supersymmetry breaking

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

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

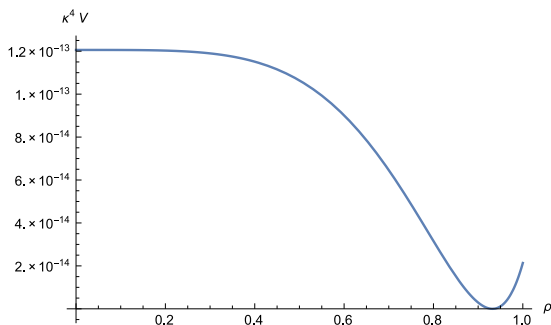
- linear superpotential  $W = f X \Rightarrow$  no  $\eta$ -problem

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

- 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



# Case 1: R-symmetry restored during inflation [11]

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

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

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

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

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

$$\mathcal{V}_D = \kappa^{-4} \frac{q^2}{2} [1 + X\bar{X}(1 + 2AX\bar{X})]^2 \quad [12]$$

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

# Case 1: predictions

slow-roll parameters

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

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

$\eta$  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  $|\eta| = 1$

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

# 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  $\rho_{\text{end}} \lesssim 1/2$

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 [20]

# Fayet-Iliopoulos (FI) D-terms in supergravity

D-term contribution: positive contribution to  $\eta \Rightarrow$  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:

$$\mathcal{L}_{\text{FI}}^{\text{new}} = \xi_1 \int d^4\theta \frac{W^2 \bar{W}^2}{\mathcal{D}^2 W^2 \bar{\mathcal{D}}^2 \bar{W}^2} \mathcal{D}W \overset{\text{gauge field-strength superfield}}{\swarrow} = -\xi_1 D + \text{fermions}$$

It makes sense only when  $\langle D \rangle \neq 0 \Rightarrow$  SUSY broken by a D-term

Supergravity generalisation: straightforward

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

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

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

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

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

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

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  $W = f X^b$  ( $W_0 = f, \kappa = 1$ )  $\Rightarrow$  [9]

# Model of inflation on D-terms

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

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

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

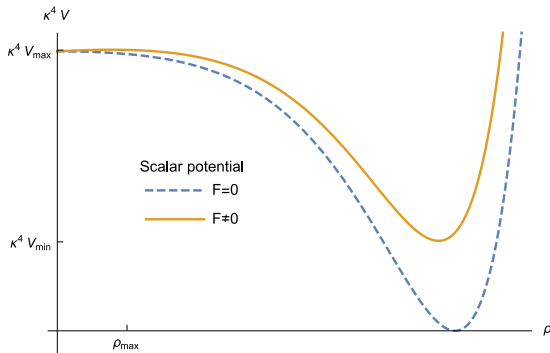
Case  $f = 0$  (pure D-term potential):

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

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

- $\xi = -1$ : 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

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

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

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

⇒ 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

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  $\Lambda$  and breaking supersymmetry

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

What about breaking SUSY with a  $\langle D \rangle$  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)

# The cosmological constant in Supergravity

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

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,  $\Lambda$  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  $\eta$ -problem, no (pseudo) scalar companion
- D-term inflation is also possible using a new FI term