Inflation and SUSY Breaking from Higher Curvature Supergravity

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CSI Corfu 2014

related work in supergravity

- Dalianis, FF, Kehagias, Riotto, von Unge, "Supersymmetry Breaking and Cosmic Inflation from Pure Supergravity," arXiv:1409.xxxx [hep-th].
- FF, Kehagias, Riotto, "On the Starobinsky Model of Inflation from Supergravity," Nucl. Phys. B **876**, 187 (2013) arXiv:1307.1137 [hep-th].
- Hindawi, Ovrut and Waldram, "Four-dimensional higher derivative supergravity and spontaneous supersymmetry breaking," Nucl. Phys. B **476**, 175 (1996) [hep-th/9511223].
- S. Cecotti, "Higher Derivative Supergravity Is Equivalent To Standard Supergravity Coupled To Matter. 1.," Phys. Lett. B **190**, 86 (1987).
- Ferrara, Grisaru and van Nieuwenhuizen, "Poincare and Conformal Supergravity Models With Closed Algebras," Nucl. Phys. B **138**, 430 (1978).

phenomenology needs

- Supersymmetry can offer answers to long-standing theoretical questions in particle physics.

Experiments and observations are pressing supersymmetry to account for more and more...

- Early time cosmology: The inflationary sector to drive inflation (or appropriate sectors for alternative models).
- LHC Physics: A hidden sector to break supersymmetry (and mediate it).
- Do we really need to introduce new sectors?

theory offers

- All supersymmetric models are coupled to supergravity.
- Supergravity is always accompanied by curvature higher derivatives.
- Higher derivative supergravity not only comes for free - it is obligatory!

Can this sector accommodate inflation / supersymmetry breaking?

- But supersymmetry breaking needs superfields.
- And inflation needs more superfields.
- Where are these superfields hidden?

outline

New DOF?

$R + R^2$ supergravity

SUSY breaking and cosmic inflation from pure supergravity

Conclusions

we start from gravity

Starobinsky '80, Whitt '84

- Higher curvature gravitation (Starobinsky model of inflation)

$$e^{-1}\mathcal{L} = -\frac{1}{2}R + \frac{\alpha}{4}R^2. \tag{1}$$

- Higher derivative but ghost free!
- We can write (1) as

$$e^{-1}\mathcal{L} = \left(-\frac{1}{2} + \frac{\alpha}{2}\varphi\right) R - \frac{\alpha}{4}\varphi^2.$$

- Finally after the rescaling the metric we find Einstein gravity coupled to a scalar (the scalaron)

$$e^{-1}\mathcal{L} = -\frac{1}{2}R - \frac{1}{2}\partial\varphi\partial\varphi - \frac{1}{4\alpha}\left(1 - e^{-\sqrt{\frac{2}{3}}\varphi}\right)^2.$$

embedding in supergravity

Two methods have been followed to embed the Starobinsky model in supergravity (in superspace)

- Couple superfields to standard supergravity and try to reproduce the potential.
- Embed the higher derivative $R + R^2$ to the minimal supergravities.
- The methods are equivalent.

Here we take the geometrical method as a guide

- We only employ the supergravity multiplet.

old-minimal supergravity multiplet

Ferrara, Nieuwenhuizen '78, Stelle, West '78

Supersymmetrization of Einstein gravity.

- The spectrum is

$$e_m^a\,,\quad \psi_m^\alpha\,,\quad M\,,\quad b_m.$$

- The supergravity Lagrangian is

$$e^{-1}\mathcal{L} = -\frac{1}{2}R + \bar{\psi}^a r_a - \frac{1}{3}M\bar{M} + \frac{1}{3}b_m b^m. \tag{2}$$

- The fields M and b_m are auxiliary fields - they are part of the supermultiplet - they don't propagate in (2).

superspace

see Gates, Grisaru, Rocek, Siegel '83, Wess, Bagger '92, Buchbinder, Kuzenko, '98

- A space with auxiliary anti-commuting coordinates.
- Manifest supersymmetry in all stages.
- In $4D$, $\mathcal{N}=1$ all we need is

$$(\mathcal{D}_C\mathcal{D}_B-(-)^{bc}\mathcal{D}_B\mathcal{D}_C)\mathrm{V}^A=-\mathcal{T}_{CB}^{D}\mathcal{D}_D\mathrm{V}^A+(-)^{d(b+c)}\mathrm{V}^D\mathcal{R}_{CBD}^{A}.$$

- Superfields contain all the components of a multiplet.

chiral superfields

- Defined as

$$\bar{\mathcal{D}}_{\dot{\alpha}}\Phi_i = 0.$$

- With chiral expansion

$$\Phi_i = A_i + \sqrt{2}\Theta^{\alpha}\psi_{\alpha\, i} + \Theta^2 F_i.$$

- The coupling to standard supergravity reads

$$\mathcal{L} = \int d^2\Theta\, 2\mathcal{E}\left[\frac{3}{8}(\bar{\mathcal{D}}^2 - 8\mathcal{R})e^{-\frac{1}{3}K(\Phi_i,\bar{\Phi}_i)} + W(\Phi_i)\right] + c.c.$$

- In component form (the bosonic sector) reads

$$\begin{aligned} e^{-1}\mathcal{L} = &- \frac{1}{2}R - K_{i\bar{j}}\partial A^i \partial \bar{A}^{\bar{j}} \\ &- e^K \left[(K^{-1})^{i\bar{j}}(W_i + K_i W)(\bar{W}_{\bar{j}} + K_{\bar{j}}\bar{W}) - 3W\bar{W}\right]. \end{aligned}$$

curvature superfields

The geometric objects of gravitation reside inside appropriate superfields.

- The Ricci superfield

$$\bar{\mathcal{D}}_{\dot{\alpha}}\mathcal{R} = 0$$

with lowest component the auxiliary field M

$$\mathcal{R}| = -\frac{1}{6}M$$

and the highest contains the Ricci scalar

$$\mathcal{D}^2\mathcal{R}| = \quad -\tfrac{1}{3}R + \tfrac{4}{9}M\bar{M} + \tfrac{2}{9}b^a b_a - \tfrac{2i}{3}e_a{}^m\mathcal{D}_m b^a + \cdots$$

curvature squared supergravity

Ferrara, Grisaru, van Nieuwenhuizen, '78, Hindawi, Ovrut, Waldram '96

- From the superfield $\mathcal{R}$ we build the superspace Lagrangian

$$-3\int d^4\theta E\mathcal{R}\bar{\mathcal{R}} = \frac{\alpha}{4}R^2 - \alpha\,\partial M\partial\bar{M} + \alpha(\nabla b)^2 + \cdots$$

- This coupling gives rise to the additional propagating scalar degrees of freedom
  - M: 2 real scalar degrees of freedom,
  - $\nabla^m b_m$: 1 real scalar degree of freedom,
  - $R^2 \rightarrow$ *scalaron*: 1 real scalar degree of freedom.

The 4 new scalar DOF reside inside appropriate superfields.

equivalent theories to HD supergravity I

Cecotti, '87

Higher derivative supergravity is equivalent to standard supergravity coupled to matter.

- The generic supergravity is

$$\mathcal{L} = -3 \int d^4\theta \, E \, f(\mathcal{R}, \bar{\mathcal{R}})$$

- Equivalent to

$$\mathcal{L} = -3 \int d^4\theta \, E \, f(\mathcal{S}, \bar{\mathcal{S}}) + \int d^2\Theta \, 2\mathcal{E} \, 6\mathcal{T} \, (\mathcal{S} - \mathcal{R})$$

  where $\mathcal{T}$ works as a Lagrange multiplier.

- The red terms contribute to the Kähler potential and the superpotential.

equivalent theories to HD supergravity II

Cecotti, '87

- From the identity

$$-6 \int d^2\Theta \, 2\mathcal{E} \, \mathcal{R}\mathcal{T} + c.c. = -3 \int d^4\theta \, E \, \left(\mathcal{T} + \bar{\mathcal{T}}\right)$$

  the remaining term is also Kähler potential.

- The HD supergravity is equivalent to standard supergravity with Kähler potential

$$K = -3 \ln \left\{\mathcal{T} + \bar{\mathcal{T}} + f\left(\mathcal{S}, \bar{\mathcal{S}}\right)\right\}$$

  and superpotential

$$W = 6\mathcal{T}\mathcal{S}.$$

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Starobinsky model from old-minimal supergravity

Kallosh, Linde '13, FF, Kehagias, Riotto '13

- The dual model is standard supergravity coupled to

$$K = -3M_P^2 \ln\left(1 + \frac{T}{M_P} + \frac{\bar{T}}{M_P} - 2\frac{S\bar{S}}{M_P^2} + \frac{\zeta}{9}\frac{S^2\bar{S}^2}{M_P^4}\right)$$

and

$$W = 6mTS.$$

- During inflation $\langle S \rangle = \langle \mathrm{Im}\, T \rangle = 0$ are strongly stabilized.
- The model becomes

$$e^{-1}\mathcal{L} = -\frac{M_P^2}{2}R - \frac{1}{2}\partial\varphi\partial\varphi - \frac{3}{2}m^2 M_P^2\left(1 - e^{-\sqrt{\frac{2}{3}}\varphi/M_P}\right)^2.$$

- Higher curvature supergravity offers for free a candidate for inflation.

- Can higher curvature supergravity do more?

the ζ-parameter

Kallosh, Linde '13

- For Starobinsky inflation the ζ parameter

$$f\left(S,\bar{S}\right) = 1 - 2\frac{S\bar{S}}{M_P^2} + \frac{\zeta}{9}\frac{S^2\bar{S}^2}{M_P^4}$$

  is chosen to be sufficiently large

$$\zeta > 3.5 \;\text{ for }\; m_S^2 > 0 \;\text{ during inflation.}$$

- For this choice there is only a single Minkowski supersymmetric vacuum.
- What happens for

$$\zeta < 3.5?$$

supersymmetry breaking from pure gravitation

Hindawi, Ovrut, Waldram '96

- If we set $\zeta = 1$ we find new vacua with

$$m_{3/2}^2 \sim m^2 \quad , \quad \langle F \rangle \sim m\, M_P.$$

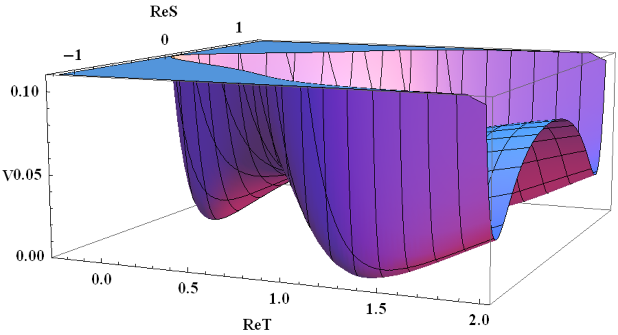

Figure: The shape of the scalar potential in units of $12 m^2 M_P^2$. The scalar fields T and S are in M_P units.

- Higher curvature supergravity has the possibility to accommodate two different sectors.
  - The inflationary sector: Starobinsky model of inflation. $\zeta > 3.5$
  - SUSY-breaking sector: Hindawi-Ovrut-Waldram supersymmety breaking. $\zeta = 1$
  - Can we combine? Not these models.
- Can higher curvature supergravity accommodate BOTH inflation and supersymmetry breaking?

generalizing higher curvature supergravity

Dalianis, FF, Kehagias, Riotto, von Unge '14

- To find the standard embedding of the Starobinsky model to supergravity we have used specific and non-generic terms

$$f\left(S,\bar{S}\right) = 1 - 2\frac{S\bar{S}}{M_P^2} + \frac{\zeta}{9}\frac{S^2\bar{S}^2}{M_P^4}.$$

- In a generic setup there will be also R-symmetry violating terms

$$f\left(S,\bar{S}\right) = 1 + \gamma\frac{S}{M_P} + \gamma\frac{\bar{S}}{M_P} - 2\frac{S\bar{S}}{M_P^2} + \frac{\zeta}{9}\frac{S^2\bar{S}^2}{M_P^4} + \cdots$$

- The origin of these models is still pure supergravitational.

supersymmetry breaking ...

We find the following vacua

- Supersymmetric Minkowski vacuum: $\langle S \rangle = \langle T \rangle = 0$
- Mikowski vacuum with broken supersymmetry: $\langle |S| \rangle \sim M_P$, $\langle T \rangle \sim M_P$.

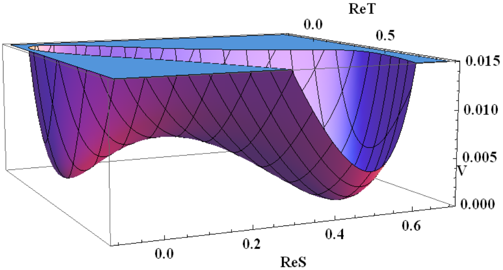

Figure: The shape of the scalar potential with $\zeta = 8$ and $\gamma = 1$ in units of $12m^2M_P^2$. The scalar fields T and S are in M_P units.

... and cosmic inflation! (compatible with PLANCK '13)

For large inflaton values the model becomes

$$e^{-1}\mathcal{L} = -\frac{M_P^2}{2}R - \frac{1}{2}\partial\varphi\partial\varphi - \frac{3}{2}m^2M_P^2\left(1-(1+4s_*)e^{-\sqrt{\frac{2}{3}}\varphi/M_P}\right)^2$$

where s_* is the value of ReS at the start of inflation.

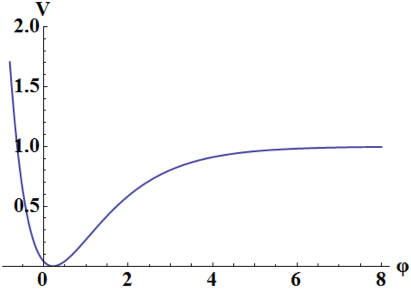

Figure: A plot of the scalar potential for large values of the inflaton field. Due to large ζ the additional scalars are strongly stabilized.

realistic models?

Dalianis, FF, Kehagias, Riotto, von Unge '14

- After slow roll the scalaron is driven towards the SUSY breaking vacuum.
- These models give a gravitino mass: $m_{3/2}^2 \sim m^2$.
- From Planck data: $m \sim 10^{-5} M_P$.
- The mediation scenario will control the scale and form of the soft terms. (see for example Hindawi, Ovrut, Waldram '96)

- Higher curvature supergravity is favored by the Planck data as a candidate for inflation.
- In addition it has a rich vacuum structure.
- R-violating terms make it possible to unify cosmic inflation and supersymmetry breaking with pure higher curvature supergravity.
- Minimal description of inflation and SUSY breaking: does not invoke any additional sector. Both are manifestations of HD supergravity.

Thank you!