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PLANCK mission, Starobinsky inflation and its realization in old-minimal supergravity

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- PLANCK mission results (March 2013)
- Starobinsky inflation and supergravity setup
- Starobinsky inflation in old-minimal supergravity
- Reheating and leptogenesis in supergravity

Our References

arXiv:1309.7494 with Takahiro Terada, to appear in JHEP

arXiv:1309.0293, to appear in PTEP

arXiv:1201.2239, invited review in Int.J.Mod.Phys. A28 (2013) 1330021

Inflation in Early Universe

- Cosmological inflation ('rapid' accelerated expansion) predicts homogeneity of our Universe at large scales, its spatial flatness, large size and entropy, and the almost scale-invariant spectrum of cosmological perturbations (in good agreement with the WMAP/PLANCK measurements of the CMB radiation spectrum).

- Inflation is a paradigm, not a theory! Known theoretical mechanisms of inflation use a slow-roll scalar field (called inflaton) with the proper scalar potential.

- The scale of inflation (about 10^{13} GeV) is well beyond the electro-weak scale (i.e. beyond the SM). Inflation is a great window to the HEP.

- The nature of inflaton and the origin of its scalar potential are unknown.

PLANCK mission data (March 2013) on CMB

combined with the WMAP9 and lensing data: Ade at al (PLANCK Collaboration], arXiv:1303.5082, and G. Hinsaw at al [WMAP Collaboration], arXiv:1212.5226:

- $n_s = 0.960 \pm 0.007$ for the CMB spectral index
- $r < 0.08$ for the CMB tensor-to-scalar-ratio (with 95% CL),
- $f_{NL} = 2.7 \pm 5.8$ (with 68% CL)

It favours the inflationary models with relatively low r and low non-Gaussianity.

Chaotic Inflation in the Starobinsky model

Viable inflationary models are easily constructed in $f(R)$-gravity theories,

$$S = -\frac{1}{2}\int d^4x\sqrt{-g}\, f(R) \tag{1}$$

The simplest (Starobinsky, 1980) model is given by ($M_{\rm Pl} = 1$)

$$f_{\rm S}(R) = R - \frac{R^2}{6M^2} \tag{2}$$

and is known as the excellent model of chaotic inflation. M coincides with the (scalaron/inflaton) mass. The model fits the observed amplitude of scalar perturbations if $M/M_{\rm Pl} \approx 3.0 \cdot 10^{-6}(50/N_e)$, and gives rise to $n_s - 1 \approx -2/N_e \approx -0.04(50/N_e)$ and $r \approx 12/N_e^2 \approx 0.004(50/N_e)^2$, in terms of the e-foldings number $N_e \approx (50 \div 55)$. It perfectly fits the PLANCK data too!

Starobinsky model and quintessence

Any $f(R)$ gravity model is classically equivalent to a quintessence model. In the special case of $f_{\rm S}(R) = R - \frac{1}{6M^2}R^2$ one finds the inflaton scalar potential

$$V(\varphi) = \frac{3}{4}M^2 \left(1 - \exp\left[-\sqrt{\frac{2}{3}}\varphi\right]\right)^2 \tag{3}$$

having a *plateau* needed for slow roll. It results in the global scale invariance in the large φ limit.

The scale invariance is *not* exact for finite values of φ, and its *violation* is measured by the *slow-roll parameters*, in full correspondence to the nearly conformal spectrum of the CMB perturbations associated with the inflaton field φ.

Pre-Comments (Introduction)

- The Starobinsky inflation is preferred by the PLANCK data. The Starobinsky model is truly non-perturbative and phenomenological.

- In the Starobinsky inflation, inflaton is scalaron (spin-0 part of metric).

- The Starobinsky inflation automatically leads to the universal reheating mechanism after inflation, in a matter-coupled $f(R)$ gravity after a transformation to the Einstein frame, with the reheating temperature $T_{\text{reh}} \approx 10^9$ GeV.

- The Higgs inflation (preferred by the PLANCK data also) leads to the *same* quintessence scalar potential but the *higher* reheating temperature (10^{13} GeV).

Some Motivation for Supergravity

- Combining SUSY with inflation requires SUGRA which is more restrictive (harder to get inflation) but more general (more particles and fields) framework.

- Deriving the Starobinsky inflation from a fundamental theory of Quantum Gravity (Superstrings), in order to upgrade its present (phenomenological) status.

- SUGRA is the LEEA of (closed) superstrings.

- Including Dark Matter (the LSP) and connecting to the MSSM.

Remarks about higher-derivative supergravity

- Available tools: (i) superconformal tensor calculus, (ii) curved superspace.

- The old-minimal and new-minimal off-shell SUGRAs are inequivalant.

- A minimal SUGRA extension of the $(R+R^2)$ gravity has 12_B+12_F d.o.f.

off-shell and, generically, 6_B+6_F d.o.f. on-shell, though the latter can be reduced to 4_B+4_F on-shell d.o.f. in a *chiral* $F(\mathcal{R})$ supergravity.

Note: the standard SUGRA (i.e. the extension of the R-gravity) has 12_B+12_F d.o.f. off-shell but only 2_B+2_F on-shell.

Old-minimal SUGRA fields and superfields

The supergravity superfield (off-shell gravity supermultiplet) $\mathcal{R}$ containing the Ricci scalar curvature R amongst its field components is covariantly chiral, $\overline{\nabla}_{\overset{\bullet}{\alpha}}\mathcal{R} = 0$, and obeys other off-shell constraints. Its bosonic field components are

$$\mathcal{R}| = X, \qquad \nabla_\alpha \nabla_\beta \mathcal{R}\Big| = \frac{1}{2}\varepsilon_{\alpha\beta}\left(-\tfrac{1}{3}R + 16\bar{X}X + \tfrac{2}{9}b_a b^a + \ldots\right), \qquad (4)$$

The old-minimal supergravity fields (in a WZ-like gauge) are $(e^a_m, \psi^\alpha_m; X, b_a)$.

There exist an invariant chiral superspace with the chiral density $\mathcal{E}$, so that

$$\mathcal{E}| = \frac{1}{2}e\,, \qquad \nabla^2\mathcal{E}\Big| = -12e\overline{X} + \ldots, \qquad (5)$$

where $e = \sqrt{-g}$. One can define the covariantly chiral projection of the $\overline{R}$ too,

$$\Sigma(\overline{R}) = -\tfrac{1}{8}\left(\overline{\nabla}^2 - 8R\right)\overline{R}\,, \qquad \overline{\nabla}_{\overset{\bullet}{\alpha}}\Sigma = 0\,. \qquad (6)$$

The SUGRA invariant actions

There are three different types of the $\mathcal{R}$-dependent invariants (Cecotti, SVK):

- of D-type, leading to the $g(X)R + h(X)R^2$ gravity,

$$S_N = \int d^4x d^4\theta \, E^{-1} N(\mathcal{R}, \overline{\mathcal{R}}) \quad , \tag{7}$$

- of F-type, leading to $g(X) + h(X)R$ gravity,

$$S_F = \int d^4x d^2\Theta \, 2\mathcal{E} F(\mathcal{R}) + \text{H.c.} \quad , \tag{8}$$

- and their extensions with a $\Sigma(\overline{R})$-dependence,

$$S_{N+F} = \int d^4x d^4\theta \, E^{-1} N(\mathcal{R}, \overline{\mathcal{R}}; \Sigma, \overline{\Sigma}) + \left[\int d^4x d^2\Theta \, 2\mathcal{E} F(\mathcal{R}, \Sigma) + \text{H.c.} \right] \tag{9}$$

Duality with matter-coupled supergravity (I)

A generic action above is dual (classically equivalent) to the standard matter-coupled SUGRA (without higher derivatives):

$$S = \int d^4x d^4\theta \, E^{-1} N(J, \overline{J}; H, \overline{H}) + \\ + \left\{ \int d^4x d^2\Theta \, 2\mathcal{E} \left[F(J, H) + \Lambda(J - \mathcal{R}) + \Xi(H - \Sigma(\overline{R})) \right] + \text{H.c.} \right\} , \tag{10}$$

where we have introduced two independent (covariantly) chiral superfields, J and H, and the covariantly chiral Lagrange multiplier superfields Λ and Ξ. Varying the action (10) with respect to Λ and Ξ yield

$$J = \mathcal{R} \qquad \text{and} \qquad H = \Sigma(\overline{R}) \tag{11}$$

respectively, which gives back the original action.

Duality with matter-coupled supergravity (II)

It its turn, the action (10) can be rewritten to

$$S = \int d^4x d^4\theta \, E^{-1} \left[N(J,\overline{J};H,\overline{H}) - (\Lambda + \overline{\Lambda}) - (\Xi\overline{J} + \overline{\Xi}J) \right] + \left\{ \int d^4x d^2\Theta \, 2\mathcal{E} \left[F(J,H) + \Lambda J + \Xi H \right] + \text{H.c.} \right\} \tag{12}$$

Comparing it with the standard matter-coupled SUGRA action in the form

$$S_{\text{msg}} = -3 \int d^4x d^4\Theta \, E^{-1} e^{-\frac{1}{3}K} + \left[\int d^4x d^2\Theta \, 2\mathcal{E}W + \text{H.c.} \right] \ , \tag{13}$$

in terms of the Kähler potential $K(\Phi,\overline{\Phi})$ and the superpotential $W(\Phi)$, we find

$$K = -3 \ln \left[\frac{\Lambda + \overline{\Lambda} + \Xi\overline{J} + \overline{\Xi}J - N}{3} \right] \tag{14}$$

and

$$W = F(J,H) + \Lambda J + \Xi H \ . \tag{15}$$

Kinetic terms and the scalar potential

The bosonic sector of the theory is given by

$$e^{-1}L_{\text{bos.}} = -\frac{1}{2}R + K_{i,\bar{j}}\partial_\mu z^i \partial^\mu \bar{z}^{\bar{j}} - V \tag{16}$$

with the scalar potential (Cremmer et al.)

$$V(z,\bar{z}) = e^G \left[G_{,i} \left(\frac{\partial^2 G}{\partial z^i \partial \bar{z}^{\bar{j}}} \right)^{-1} G_{,\bar{j}} - 3 \right] \tag{17}$$

where we have introduced the notation

$$\Lambda| = z^1 \, , \quad J| = z^2 \, , \quad \Xi| = z^3 \, , \quad H| = z^4 \, , \qquad i,j = 1,2,3,4 \tag{18}$$

and the Kähler gauge-invariant function

$$G = K + \ln(\overline{W}W) \, , \qquad G_{,i} = \frac{\partial G}{\partial z^i} \, , \qquad G_{,\bar{j}} = \frac{\partial G}{\partial \bar{z}^{\bar{j}}} \, . \tag{19}$$

Some results of our detailed studies

- The Kähler potential in Eq. (14) is of the no-scale type, favoured in many superstring compactifications, and often used for a dynamical solution to the hierarchy problem between M_{H} and M_{Pl}.

- A non-trivial $\Sigma(\overline{R})$-dependence leads to ghosts and should be discarded.

- An F-type action can be included into a D-type action, except of a constant.

- An F-type constant triggers spontaneous SUSY breaking of arbitrary scale.

Embedding the Starobinsky inflation into supergravity

- Choosing $N = \lambda \overline{J} J$ with $F'(J) = -1/2$ generates the Starobinsky scalar potential in the parametrization $\Lambda = \frac{1}{2} \exp[\sqrt{\frac{2}{3}}\phi] + ib$ along the inflationary trajectory $J = b = 0$ (Cecotti). However, this trajectory is unstable w.r.t. J.

- Stabilization can be achieved by modifying $N(\overline{J}J) = \lambda \overline{J} J - \zeta(\overline{J}J)^2$ for appropriate values of the positive parameter ζ (Kallosh, Linde et al).

- The $F(\mathcal{R})$ supergravity model with a cubic F function leads to the high-curvature inflation (Ketov, Starobinsky). However, it is unstable w.r.t. R.

- No-scale supergravities with the $SU(N,1)/SU(N)\times U(1)$ Kähler potential and special superpotential also allow the Starobinsky inflation (Ellis et al).

Reheating and gravitino leptogenesis

- Scalaron is universally coupled to ALL matter, so that reheating can proceed through the out-of-equlibrium scalaron decay.

- The scale of SUSY breaking is directly related to the gravitino mass.

- Gravitino interactions have the gravitational strength and can generate CP-asymmetry carried by sleptons. Hence, gravitino may produce L-asymmetry too. It requires the high scale of SUSY breaking, $M_S \geq 10^{13}$ GeV (Krauss at al).

- Then gravitino is heavy, $m_{3/2} \geq 10^8$ GeV, so the gravitino problem does not arise. The reheating temperature after inflation is $T_{reh} \geq 10^{12}$ GeV.

Conclusion and Outlook

The story of the Starobinsky inflation, reheating, and leptogenesis in supergravity is fascinating and still unfinished.

Thank you for your attention!