Higher Curvature Supergravity and Cosmology

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Motivation

- A flat FRW Universe is extremely fine tuned solution in GR.
- The simplest idea to solve this puzzle is a rapid expansion of our universe driven by the vacuum energy: Inflation.
- Inflation can be implemented by a scalar field

$$e^{-1}\mathcal{L} = \frac{1}{2}M_P^2 R - \frac{1}{2}\partial\varphi\partial\varphi - V(\varphi)$$

when it is slow-rolling

$$\begin{aligned} \epsilon &= \frac{1}{2}M_P^2\left(\frac{V'}{V}\right)^2 \ll 1 \\ |\eta| &= M_P^2\left|\frac{V''}{V}\right| \ll 1. \end{aligned}$$

Constraints on inflation

Planck collaboration '13

- Spectral index: $1 - n_s = 6\epsilon - 2\eta$.
- Tensor to scalar ratio: $r = 16\,\epsilon$.

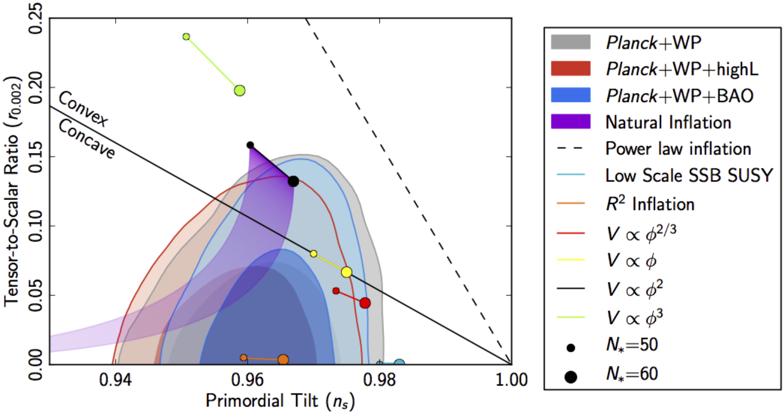


Figure: Tensor to scalar ratio from Planck satellite.

Starobinsky model of inflation

Starobinsky '80, Whitt '84

- Higher curvature gravitation

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

- Higher derivative but ghost free!
- We can write 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 $R + R^2$ in supergravity

There exist more than one flavor of minimal supergravities; they have different distribution of the auxiliary degrees of freedom.

- Old-minimal supergravity. *Ferrara, Nieuwenhuizen ’78, Stelle, West ’78*
- New-minimal supergravity. *Sohnius, West ’81*

The two formulations are dual when there exist no curvature higher derivatives $\rightarrow$ Standard supergravity. *Ferrara, Girardello, Kugo, Van Proeyen ’83*

- There exist also non-minimal supergravities.

$R + R^2$ in old-minimal supergravity

Old-minimal supergravity

- The supergravity Lagrangian is

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

Ferrara, Nieuwenhuizen '78, Stelle, West '78, Wess, Zumino '78

- From the Ricci superfield $\mathcal{R} \sim \Theta^2 R$ we build

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

Ferrara, Grisaru, van Nieuwenhuizen '78, Theisen '85, Hindawi, Ovrut, Waldram '96

The 4 new scalar DOF due to SUSY have to reside inside appropriate superfields: $\mathcal{T}$ and $\mathcal{S}$.

Equivalence to standard supergravity

Cecotti '87

- The generic $R + R^2$ 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.

- This is 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

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

Starobinsky model from old-minimal supergravity

- For the Starobinsky model the equivalent description is standard supergravity coupled to

$$K = -3M_P^2 \ln\left(1 + \frac{T}{M_P} + \frac{\bar{T}}{M_P} - 2\frac{S\bar{S}}{M_P^2} + \frac{\zeta}{9}\frac{S^2\bar{S}^2}{M_P^4}\right)\ , \quad W = 6mTS.$$

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

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

with supersymmetric vacuum. *Kallosh, Linde '13, FF, Kehagias, Riotto '13*

- Breaking the R-symmetry leads to vacua with broken supersymmetry. *Dalianis, FF, Kehagias, Riotto, von Unge '14*

$R + R^2$ in new-minimal supergravity

New-minimal supergravity

- The supergravity Lagrangian is ($H = *dB$)

$$e^{-1}\mathcal{L} = -\frac{1}{2}M_P^2\, R + \bar{\psi}^a r_a + 2M_P^2\, A_a H^a - 3M_P^2\, H_a H^a .$$

Sohnius, West '81, Ferrara, Sabharwal '89

- From $V_{\rm R} \sim \theta^2\bar{\theta}^2\, R$ we can built

$$-\frac{\alpha}{4}\int d^2\theta\, \mathcal{E}\, W^2(V_{\rm R}) \to \alpha e R^2 - \frac{1}{4}\alpha e F^2(A_m) + \cdots$$

Cecotti, Ferrara, Porrati, Sabharwal '88

The vector will become massive via a Stueckelberg mechanism. *Cecotti, Ferrara, Girardello '87*

Starobinsky model from new-minimal supergravity

- The bosonic sector of $R + R^2$ new-minimal supergravity is equivalent to

$$
\begin{aligned}
e^{-1}\mathcal{L} = & -\frac{1}{2}M_P^2 R - \frac{1}{4g^2}F^{mn}F_{mn} - \frac{1}{2}\partial_m\phi\partial^m\phi \\
& - 3M_P^2 e^{-2\sqrt{\frac{2}{3}}\phi/M_P}\left(\partial_m a + A_m\right)^2 \\
& - \frac{9}{2}g^2 M_P^4\left(1 - e^{-\sqrt{\frac{2}{3}}\phi/M_P}\right)^2 .
\end{aligned}
$$

  FF, Kehagias, Riotto '13

- New class of inflationary single field models. *FF, Kehagias, Riotto '13, Ferrara, Kallosh, Linde, Porrati '13, Ferrara, Porrati '14, FF, von Unge '14*

Open issues in the Starobinsky model

What if we include higher order corrections?

FF, Kehagias, Riotto '13, Kamada, Yokoyama '14

$$\xi \int d^4\theta\, \mathcal{D}^\alpha S \mathcal{D}_\alpha S\, \bar{\mathcal{D}}_{\dot\alpha} \bar{S} \bar{\mathcal{D}}^{\dot\alpha} \bar{S} \;\rightarrow\; \xi R^4 .$$

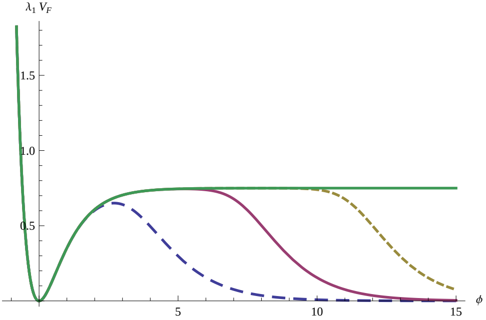
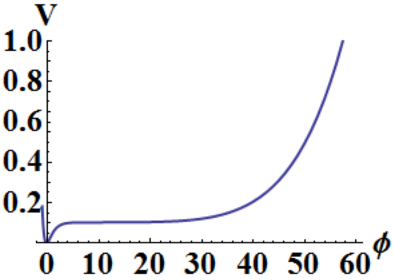


Figure: The scalar potential for three different values of $s = \xi/\lambda_1^3$: *i*) $s = 10^{-4}$ (long dashed line), *ii*) $s = 10^{-8}$ (continuous line) and *iii*) $s = 10^{-12}$ (short dashed line). The horizontal line corresponds to $\xi = 0$.

Initial conditions need tuning

Goldwirth, Piran, '91, Ijjas, Steinhardt, Loeb, '13

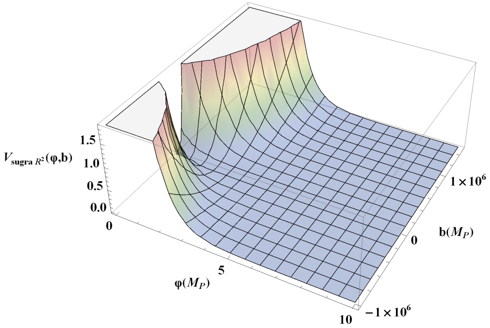
- The standard lore is that inflation starts from $\rho \sim M_P^4$.
- Lower $\rho_{\text{inflation starts}} \to$ bigger initial homogeneous region.
- For Starobinsky inflation starts at $\rho \sim 10^{-10} M_P^4$.
- Give up pure $R + R^2$ description?



What does $R + R^2$ supergravity do for free?

Dalianis, FF '15

- The propagating auxiliary fields make M_P^4 energy densities accessible (with energy equipartition).
- Before inflation: Kinetic energy - Potential energy balance.
- Significantly relaxes the required tuning of the initial conditions.



Summary - Outlook

- We presented the structure of the 12/12 $R + R^2$ supergravity.
- By supersymmetry they have to give rise to additional propagating modes - they arise from auxiliary fields.
- The propagating modes endow the models with new properties
  - They can lead to SUSY breaking after inflation. *Dalianis, FF, Kehagias, Riotto, von Unge '14*
  - They reduce the amount of fine tuning required in the initial conditions for inflation. *Dalianis, FF '15*
- Other supergravity theories?

For the $R + R^2$ non-minimal (20/20) supergravity we find

- 2 non-ghost massive chiral multiplets of equal mass (Dirac mass).
- 1 non-ghost massive vector multiplet.
- 1 ghost massive vector multiplet (and tachyonic).

All multiplets have equal mass at the linearized level.
FF, Kehagias, Koutrolikos '15

Thank you!