Unified No-Scale Inflation

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Based on work with John Ellis, Dimitri Nanopolous and Keith Olive
arXiv:1903.05267

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Goals

- Introduce a viable model of inflation in a no-scale supergravity framework.

$$n_s < 0.9649 \pm 0.0042 \qquad r_{0.002} < 0.10$$

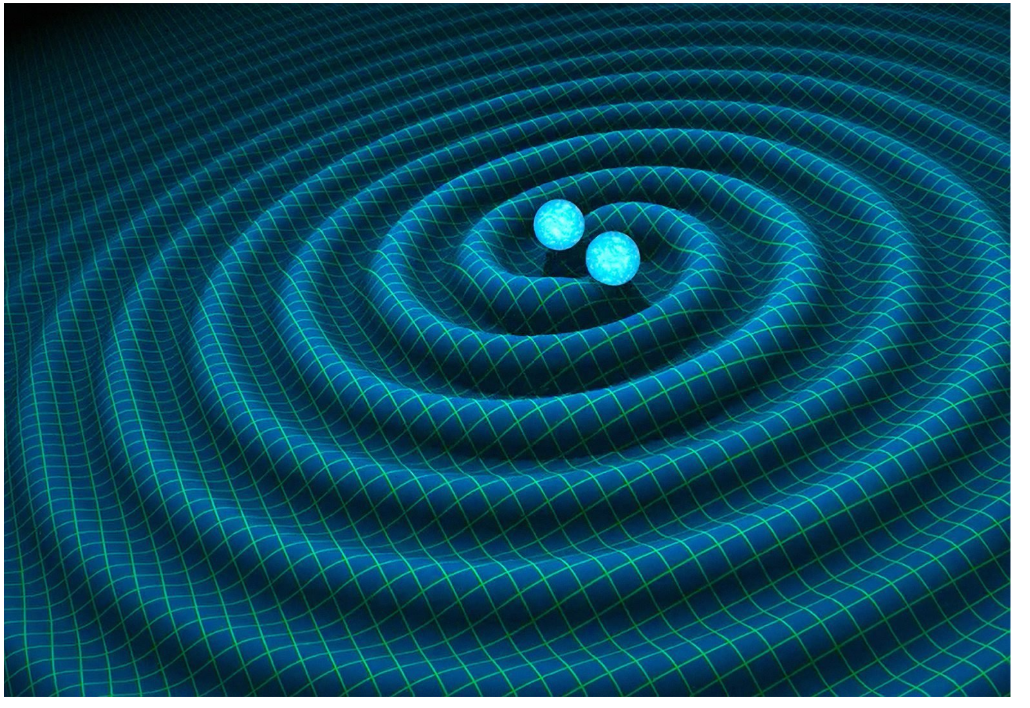
- Incorporate an adjustable scale for supersymmetry breaking.

- Obtain a value of the cosmological constant comparable to the present value:

$$V \sim 10^{-120}$$

Motivations for supergravity

- Supergravity unifies supersymmetry with general relativity.
- Arises naturally from local supersymmetry.
- Predicts a supersymmetric partner of graviton, which is known as gravitino.



Inflation

Planck Data gives constraints on inflation. → *We need cosmological models that agree with experiment.*

- Accelerated expansion:

$$\epsilon = -\frac{\dot{H}}{H^2} = -\frac{d\ln H}{dN} < 1$$

N is the number of e-folds of inflationary expansion

$$dN = d\ln a$$

- Slow-roll inflation.

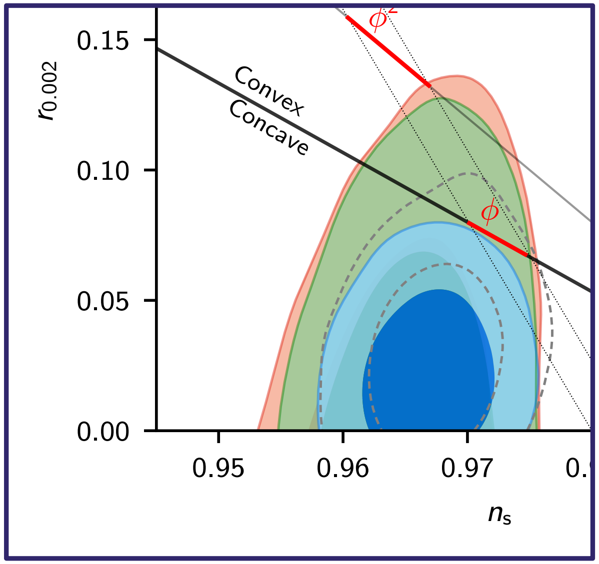
$$\epsilon \approx \frac{1}{2}\left(\frac{V_\phi}{V}\right)^2 \quad \eta \approx \frac{V_{\phi\phi}}{V}$$

- Slow-roll Parameters:

$$n_s = 1 - 6\epsilon + 2\eta$$
$$r = 16\,\epsilon$$

Quantum fluctuations are created ~50-60 e-folds before the end of inflation.

Scalar potential V must satisfy Planck data.



Inflation in Supergravity

- Measurements of the CMB favor the $R + R^2$ models

$$V = \frac{3}{4} M^2 \left(1 - e^{-\sqrt{2/3}\varphi}\right)^2$$

Starobinsky, '80

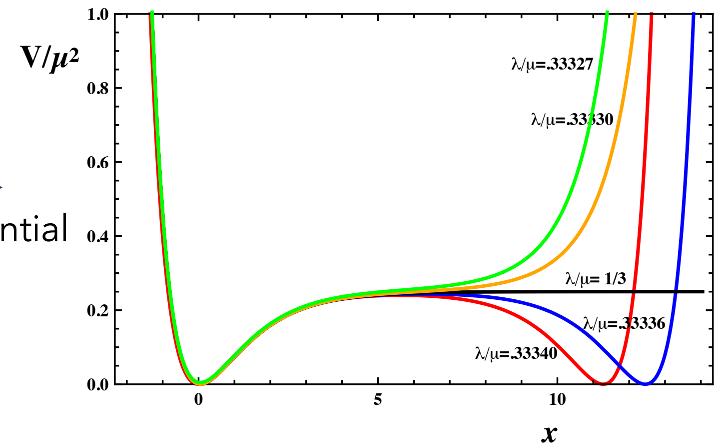
- The nominal choice of $N = 55$ yields $n_s = 0.965$ and $r = 0.0035$.

Consistent with all experimental measurements!

Most importantly, can this be realized in theories of supergravity?

No-Scale Supergravity Framework

/w Wess-Zumino Superpotential



Ellis, Nanopoulos, Olive, '13

The answer is YES!

The Recipe

- We start with the following Kähler potential: → $K = -3\log\left(T + T^* - \frac{|\phi|^2}{3}\right)$

Combine it with the Wess-Zumino Superpotential:

$$W = M\left(\frac{\phi^2}{2} - \frac{\phi^3}{3\sqrt{3}}\right)$$

$$V = e^G\left[\frac{\partial G}{\partial \phi^i} K^i_{j*} \frac{\partial G}{\partial \phi^*_j} - 3\right]$$

where $G \equiv K + \ln W + \ln W^*$

$\langle Re\ T\rangle = \frac{1}{2}$

$\langle Im\ T\rangle = 0$

Use the canonical field parametrization

$\phi = \sqrt{3}\tanh\left(\frac{x}{\sqrt{6}}\right)$

$x \in \mathbb{R}$

$$V = \frac{3}{4}M^2\left(1 - e^{-\sqrt{2/3}x}\right)^2$$

We obtain the Starobinsky model in no-scale supergravity!

Missing Components

We also want:

- Introduce a positive cosmological constant $V \sim 10^{-120}$
- Introduce an adjustable scale for supersymmetry breaking
- Incorporate modulus fixing

Unified No-Scale Supergravity Models

But small steps first…

Find the de Sitter vacua solutions for a single field → Extend it to multi-field models.

Constructing Minkowski Vacua

- Introduce the Kähler potential: $K = -3\,\alpha \ln\left(T + T^* + \beta\,(T - T^*)^4\right)$

  (α) Arbitrary curvature parameter

  (β) Quartic stabilization in the imaginary direction terms.

- We assume that $\langle Im\ T \rangle = 0$

- Choose the following ansatz for superpotential:

$$W = \lambda\,T^n$$

Gives two possible solutions

$$W = \lambda\,T^{\frac{3}{2}(\alpha - \sqrt{\alpha})}$$

$$W = \lambda\,T^{\frac{3}{2}(\alpha + \sqrt{\alpha})}$$

Both solutions yield Minkowski vacuum

$$V = 0$$

Ellis, Nagaraj, Nanopoulos, Olive, '18

Constructing de Sitter Vacua

- We have found that:

$$W = \lambda T^{n_\pm} \quad \text{with} \quad n_\pm = \frac{3}{2}\left(\alpha \pm \sqrt{\alpha}\right) \quad \text{gives} \quad V = 0$$

- But if we combine two different Minkowski vacua solutions and form a superpotential pair:

$$W = \lambda_1 T^{n_-} - \lambda_2 T^{n_+} \longrightarrow \boxed{V = 12\,\lambda_1 \lambda_2}$$

We can consider the following cases:

- When λ_1 and λ_2 are of the same sign, we recover dS vacua.
- When λ_1 and λ_2 are of the opposite sign, we recover AdS vacua.
- When either λ_1 and λ_2 is zero, we recover Minkowski vacua.

We obtain a non-vanishing cosmological constant!

Multi-Field Models

- We cannot recover Starobinsky-like inflation for a single field → Need to consider the multi-field models.
- Introduce the following multi-field Kähler potential:

$$K = -3\,\alpha\,\ln\left(T + T^* - \sum_{i=1}^{N-1} \frac{|\phi_i|^2}{3} + \beta\,(T - T^*)^4\right)$$

- We once again assume that all our fields are real.
- Define the argument inside the logarithm when the fields are real as:

$$\xi = 2T - \sum_{i=1}^{N-1} \frac{\phi_i^2}{3}$$

A positive cosmological constant!

$$W = \lambda_1\,\xi^{n_-} - \lambda_2\,\xi^{n_+} \longrightarrow V = 12\,\lambda_1\lambda_2$$

Ellis, Nanopoulos, Olive, Verner, '19

Supersymmetry Breaking

- We expect additional contributions to the vacuum density from gauge phase transitions

$$\Lambda = 12\,\lambda_1\lambda_2$$

Include the symmetry breaking contributions

Electroweak contribution

$$\sim 10^{-60}$$

$$\lambda_1 \sim 10^{-15} \qquad \lambda_2 \sim 10^{-45}$$

- If we assume that at the minimum the fields obtain the following VEVs:

$$\langle T \rangle = \tfrac{1}{2} \qquad \langle \phi_i \rangle = 0$$

GUT transition

$$\sim 10^{-30}$$

$$\lambda_1 \sim \lambda_2 \sim 10^{-15}$$

- The SUSY breaking through F-terms is given by:

$$\sum_{i=1}^{N} |F_i|^2 = F_T^2 = \frac{(\lambda_1+\lambda_2)^2}{\alpha}$$

Both constants are of the same order!

Unified No-Scale Models

- We can now consider a unified no-scale model.
- The full Kähler potential is given by:

We include stabilization terms in both real and imaginary directions.

$$K = -3 \ln \left(T + T^* - \frac{|\phi_i|^2}{3} + \beta \left(T - T^* \right)^4 + \gamma \left(T + T^* - 1 \right)^4 \right)$$

We set a curvature parameter to $\alpha = 1$

- The full superpotential is given by:

$$W = W_{dS} + W_{Inf}$$

W_{dS}:

$$\lambda_1 - \lambda_2 \left(2T - \frac{\phi^2}{3} \right)^3$$

At the minimum gives $m_{3/2} = \lambda_1 - \lambda_2 \sim TeV$

W_{Inf}:

$$M \left(\frac{\phi^2}{2} - \frac{\phi^3}{3\sqrt{3}} \right)$$

Wess-Zumino Superpotential

Scalar Potential

- We acquire the following scalar potential form:

Mixing term, which does not affect the inflationary dynamics

$$V = 12\lambda_1\lambda_2 + 12\lambda_2 M\left(\frac{\phi^2}{2} - \frac{\phi^3}{3\sqrt{3}}\right) + 3M^2\left(\frac{\phi}{\sqrt{3}+\phi}\right)^2$$

Positive cosmological constant.

Starobinsky Inflationary potential

- At the minimum:

$$\langle\phi\rangle = 0$$
$$\langle T\rangle = \frac{1}{2}$$
$$\Lambda = 12\,\lambda_1\lambda_2$$
$$|F_T| \neq 0$$

→ Fields associated with T decay into a gravitino pair.

→ The problem of entropy production is evaded for strong moduli stabilization.

Conclusion

- We have successfully introduced a unified no-scale model that incorporates:
  - Inflation
  - Modulus fixing
  - Supersymmetry breaking
  - Positive Cosmological Constant
- In this simple model we set a curvature parameter $\alpha = 1$ but the unified no-scale models can be extended to $\alpha \neq 1$:

$$V = \frac{3}{4} M^2 \left(1 - e^{-\sqrt{\frac{2}{3\alpha}}x}\right)^2$$

- Models can be extended to include matter fields by introducing a Standard Model-like superpotential.