Higgs inflation and gravitational degrees of freedom

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Using what you have

$$S = \int d^4x \sqrt{-g} \left(\frac{1+\xi\phi^2}{2} g^{\alpha\beta} R_{\alpha\beta} - \frac{1}{2} g^{\alpha\beta} \nabla_\alpha \phi \nabla_\beta \phi - V(\phi) \right)$$

$$V(\phi) = \frac{\lambda}{4} \phi^4$$

- Inflation with the Standard Model Higgs uses the only known scalar field that may be elementary. (Bezrukov and Shaposhnikov: 0710.3755)
- Non-minimal coupling $\xi\phi^2$ makes the Einstein frame potential exponentially flat.
  - The coupling constant ξ only affects the amplitude.
  - Reheating is known, so no ambiguity in N. (Figueroa et al: 1504.04600)
- The classical predictions are in excellent agreement with observations: $n_s = 0.96$, $r = 5 \times 10^{-3}$.

When the action is not enough

- Complication: classical low-energy action is not enough to specify the theory.

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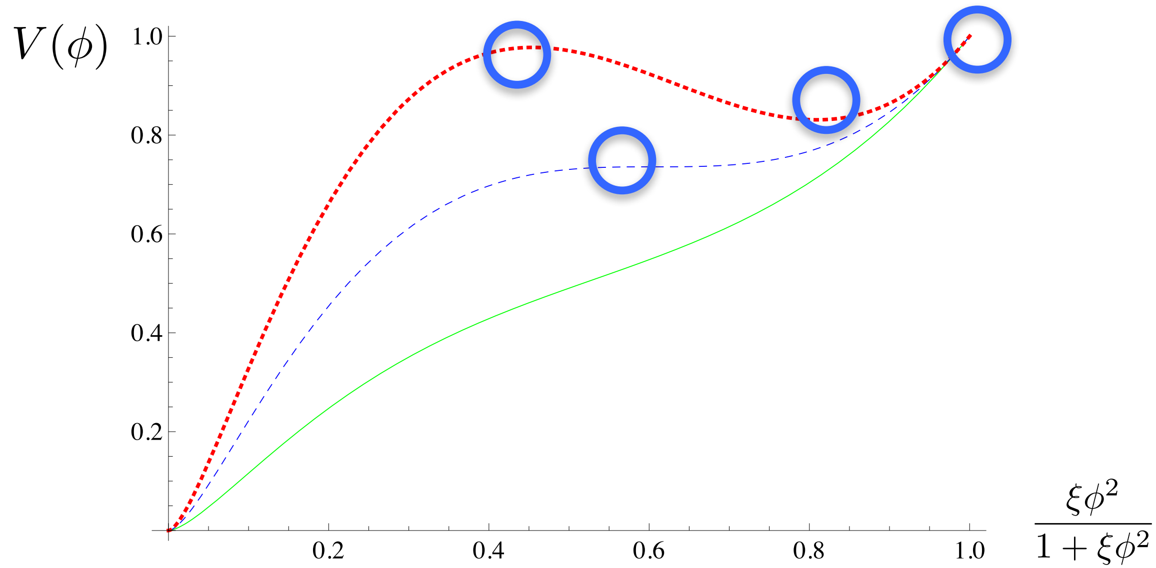
- Two sources of ambiguity.
  - Quantum theory: how to calculate loop corrections?
  - General relativity: what are the gravitational degrees of freedom?

Loop-corrected potential



- Different inflationary possibilities:
  - Plateau: apparently not spoiled by loops.
  - Inflection point: can give $r \sim 0.1$.
  - False vacuum: new physics needed for graceful exit.
  - Hilltop: under investigation. (Enckell, Enqvist, SR, **Tomberg**)

The many faces of Einstein gravity

$$S=\int \mathrm{d}^4x\sqrt{-g}\left(\frac{1+\xi\phi^2}{2}g^{\alpha\beta}R_{\alpha\beta}(g,\partial g,\partial^2 g)-\frac{1}{2}g^{\alpha\beta}\nabla_\alpha\phi\nabla_\beta\phi-V(\phi)\right)$$

- Usually the gravitational degrees of freedom are taken to be the metric and its first derivative.
- In the Palatini formalism, the metric and the connection are independent degrees of freedom.
- In the Einstein-Hilbert case, metric and Palatini formalisms are equivalent.
- With a non-minimally coupled scalar field, they give different physical theories. (Bauer and Demir: 0803.2664)

The many faces of Einstein gravity

$$S = \int \mathrm{d}^4x \sqrt{-g} \left(\frac{1+\xi\phi^2}{2} g^{\alpha\beta} R_{\alpha\beta}(\Gamma, \partial\Gamma) - \frac{1}{2} g^{\alpha\beta} \nabla_\alpha \phi \nabla_\beta \phi - V(\phi) \right)$$

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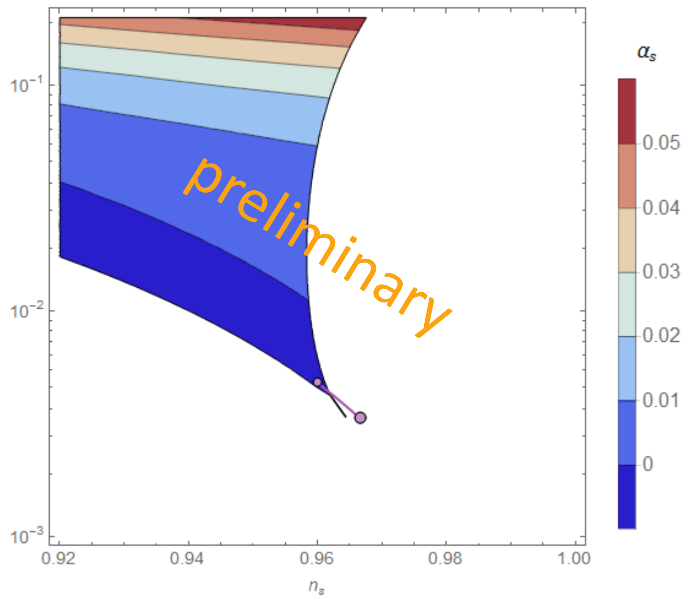
Metric vs. Palatini

$$S = \int \mathrm{d}^4x \sqrt{-g} \left(\frac{1 + \xi\phi^2}{2} g^{\alpha\beta} R_{\alpha\beta}(\Gamma, \partial\Gamma) - \frac{1}{2} g^{\alpha\beta} \nabla_\alpha \phi \nabla_\beta \phi - V(\phi) \right)$$

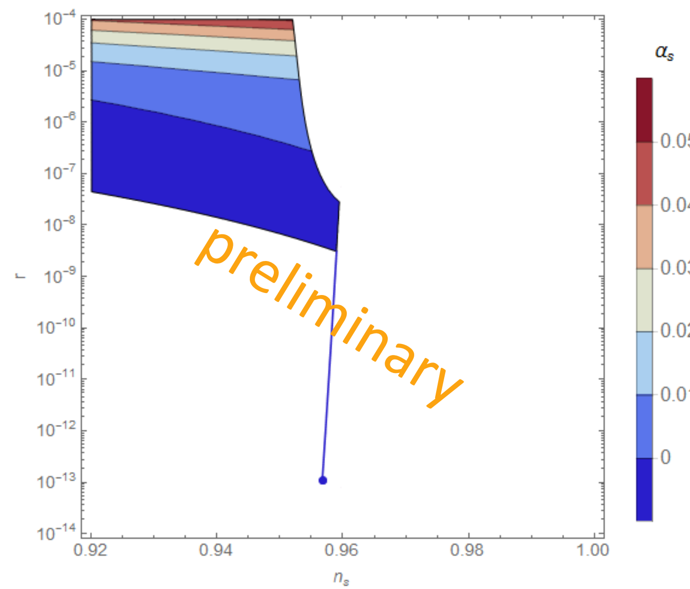
- In both cases, the Einstein frame is reached with the conformal transformation $g_{\alpha\beta} = (1 + \xi\phi^2)^{-1} \tilde{g}_{\alpha\beta}$
- In the Palatini case, the conformal transformation does not affect the Ricci tensor.
- Therefore we get a different Einstein frame potential.
- On the plateau, both give $n_s = 1 - 2/N = 0.96$, but r is different:
  - Metric: $r = 12/N^2 = 5\times10^{-3}$
  - Palatini: $r = 2/(\xi N^2) = 8\times10^{-4}/\xi$ ($\lambda/\xi = 10^{-10}$)

Inflection point inflation: metric vs. Palatini



metric

(SR and Wahlman)



Palatini

(Colour shows the running of the spectral index $\alpha_s = 0.01 \pm 0.01$.)

- Metric formulation range of *r* is within reach of next generation experiments, Palatini not.

Higgs at the crossroads of quantum theory and gravity

- Higgs inflation uses only the known particle physics and gravitational degrees of freedom.
- Metric formalism value for *r* will be tested by next generation CMB experiments.
- The issue of quantum corrections is not settled.
  - Consistency conditions between cosmology and colliders.
- Have to specify the gravitational degrees of freedom.
  - Formulations that are equivalent for Einstein gravity differ when there is a non-minimally coupled scalar: Palatini, teleparallel, ...
  - CMB observations can be used to determine the gravitational degrees of freedom.