Higgs inflation: connecting electroweak physics to inflation

(work with Vera-Maria Enckell, Kari Enqvist, Sami Raatikainen, Eemeli Tomberg and Lumi-Pyry Wahlman)

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Using what you have

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\mathrm{Pl}}^2 + \xi h^2}{2}R - \frac{1}{2}g^{\alpha\beta}\partial_\alpha h\partial_\beta h - V(h)\right]$$

$$V(h) = \frac{\lambda}{4}(h^2 - v^2)^2 \simeq \frac{\lambda}{4}h^4$$

- Non-minimal coupling $\xi h^2 R$ is the only new dimension 4 term for the combined Einstein-Hilbert + SM action.

- The coupling ξ is generated by renormalisation, even if it is classically zero.

- Non-minimal coupling enables Higgs inflation, which uses the only known scalar field that may be elementary.
(Bezrukov and Shaposhnikov: 0710.3755)

When the action is not enough

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\mathrm{Pl}}^2 + \xi h^2}{2}R - \frac{1}{2}g^{\alpha\beta}\partial_\alpha h \partial_\beta h - V(h)\right]$$

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

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

Two aspects of spacetime

- There are different formulations of general relativity (GR).
- They are not modified theories, but alternative theories.
- In general, metric and connection are independent degrees of freedom.
- Metric describes distances in spacetime and inner products of vectors.
- Connection describes straight lines in spacetime and derivatives of vectors.

Metric and Palatini

- One formulation of GR is the metric formulation (1915), where the connection is defined in terms of the metric.

- Another is the Palatini formulation (1925), where the connection is determined by the field equations, instead of being constrained a priori.

- For the Einstein-Hilbert action R, the formulations are equivalent.

Higgs breaks the equivalence

- Different formulations of GR are inequivalent if the gravity action is more complicated than *R* or matter couples to the connection.
- Higgs exists, so nature is described by a scalar-tensor theory.
- Higgs couples to the connection, breaking the equivalence between the formulations. (Bauer and Demir: 0803.2664)

Two faces of Einstein gravity

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

- The Einstein frame is reached with the conformal transformation $g_{\alpha\beta} \to (1+\xi h^2)^{-1}g_{\alpha\beta}$
- In the Palatini case, the conformal transformation does not affect the Ricci tensor.
- To recover canonical kinetic term, define new field χ:
  - metric: $\frac{\mathrm{d}\chi}{\mathrm{d}h} = \sqrt{\frac{1+\xi h^2+6\xi^2h^2}{(1+\xi h^2)^2}} \simeq \frac{\sqrt{6}}{h} \Rightarrow h \propto e^{\chi/\sqrt{6}}$
  - Palatini: $\frac{\mathrm{d}\chi}{\mathrm{d}h} = \sqrt{\frac{1+\xi h^2}{(1+\xi h^2)^2}} \simeq \frac{1}{\sqrt{\xi}h} \Rightarrow h \propto e^{\sqrt{\xi}\chi}$
- Polynomials are transformed into sums of exponentials.

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Two faces of Einstein gravity

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- Polynomials are transformed into sums of exponentials.

Higgs potential in Metric vs Palatini

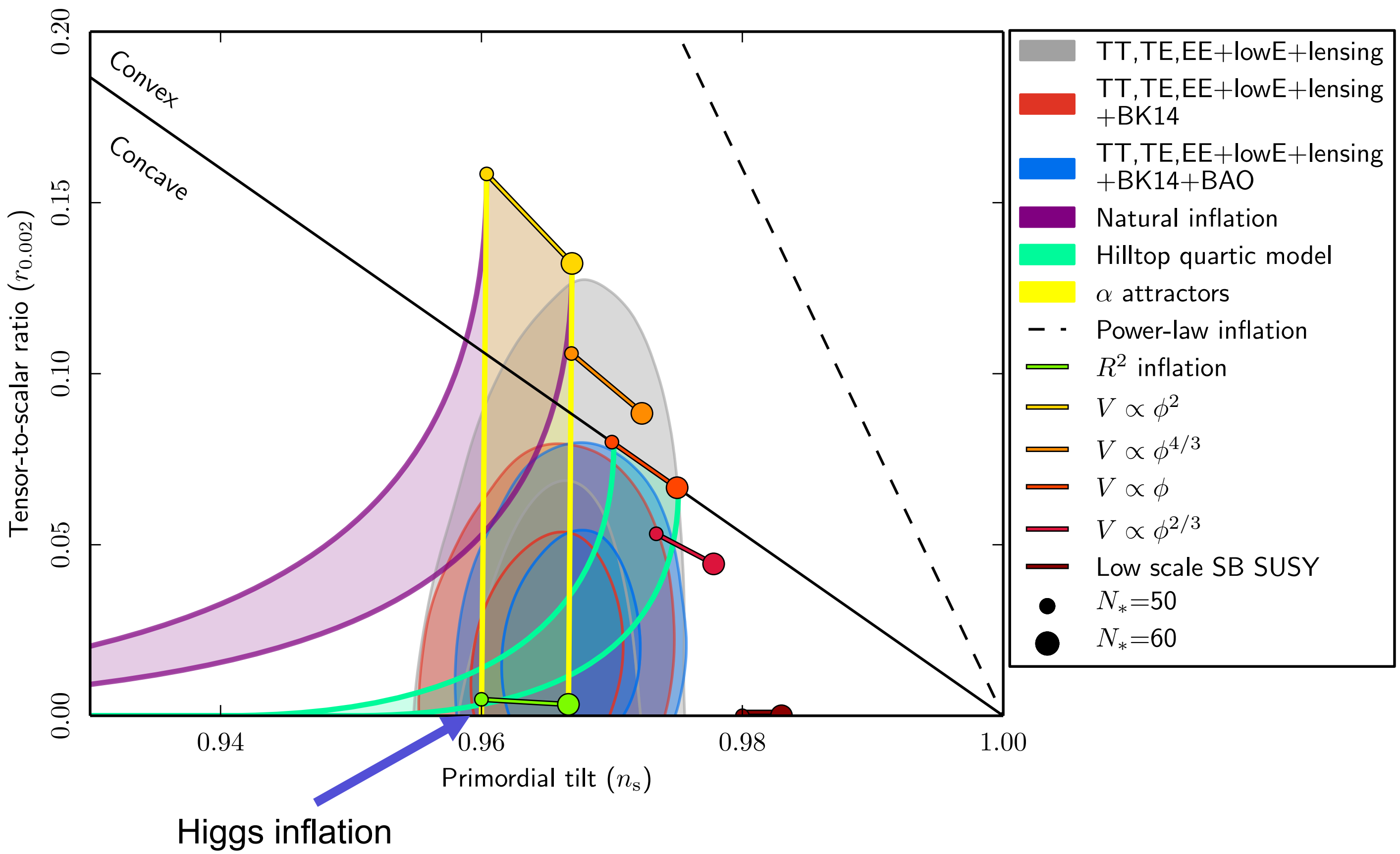
$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}g^{\alpha\beta}\partial_\alpha\chi\partial_\beta\chi - U(\chi)\right]$$

- We get a different Einstein frame potential depending on the formulation of GR:
  - metric: $U(\chi) \equiv \frac{V[h(\chi)]}{[1+\xi h(\chi)^2]^2} \simeq \frac{\lambda}{4\xi^2}(1 - 2e^{-\frac{2}{\sqrt{6}}\chi})$
  - Palatini: $U(\chi) \simeq \frac{\lambda}{4\xi^2}(1 - 8e^{-2\sqrt{\xi}\chi})$
- The potential is exponentially flat.

Predictions of Higgs inflation on the plateau

- Predictions for inflation depend on reheating.
- This is the SM, so reheating is known. (Garcia-Bellido, Figueroa and Rubio: 0812.4624, Rubio and Tomberg: 1902.10148)
  - metric: $n_s = 0.96 \; , \; r = 5 \times 10^{-3} \; , \; \xi = 4 \times 10^4 \sqrt{\lambda}$
  - Palatini: $n_s = 0.96, \; r = \frac{8 \times 10^{-4}}{\xi} = \frac{8 \times 10^{-14}}{\lambda} \; , \; \xi = 10^{10} \lambda$

The data likes Higgs inflation



Planck: arXiv:1807.06211

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Renormalising the non-renormalisable

- Dimension 4 is key for flat potential: $U(\chi) = \frac{V[h(\chi)]}{[1+\xi h(\chi)^2]^2} \simeq \frac{\frac{\lambda}{4}h^4}{\xi^2 h^4}$
- Due to loop corrections, inflationary predictions in principle depend on Higgs and top mass.
  - Consistency condition between cosmology and colliders?
- Due to gravity, the theory is not renormalisable.
  - Loop corrections boil down to prescriptions.
- Perturbative unitarity is violated at scales below M_{Pl}:

$1/\xi \text{ (metric) or } 1/\sqrt{\xi} \text{ (Palatini)} \sim 10^{14} \text{ GeV}$

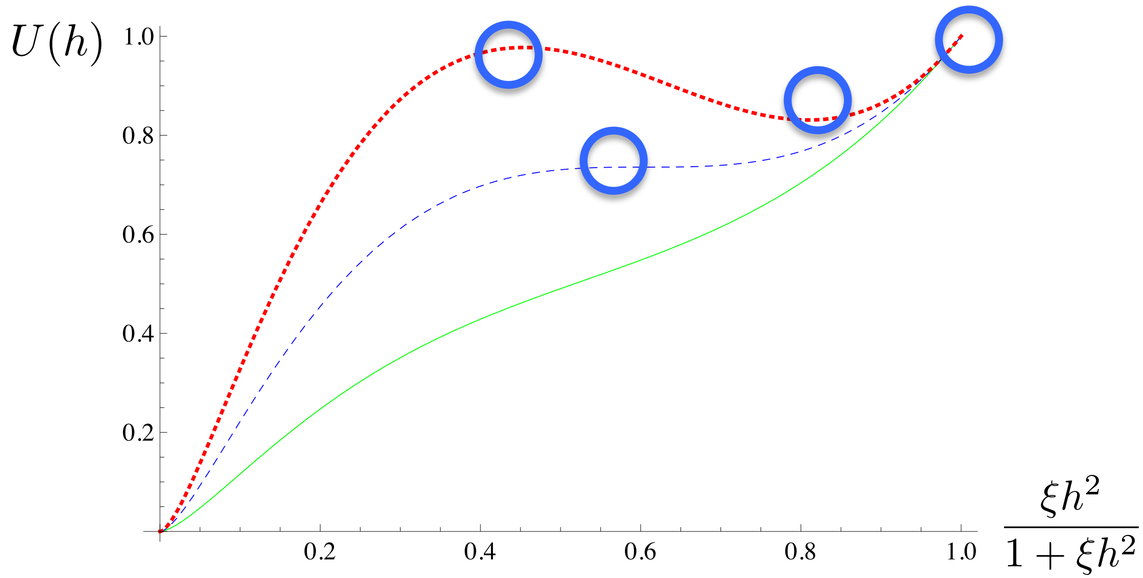
- Loop corrections can also open up new inflation regimes.

Higgs window to gravity

- Higgs inflation is a minimal bottom-up scenario for particle physics and gravity, using only known degrees of freedom.
- Different formulations of GR become inequivalent as Higgs couples to the connection.
- Predictions of Higgs inflation depend on the choice of theory of gravity and loop corrections.
  - Observations can tell what are the gravitational degrees of freedom.
- Different results for teleparallel formulation, loop quantum gravity action, ...

Backup slides

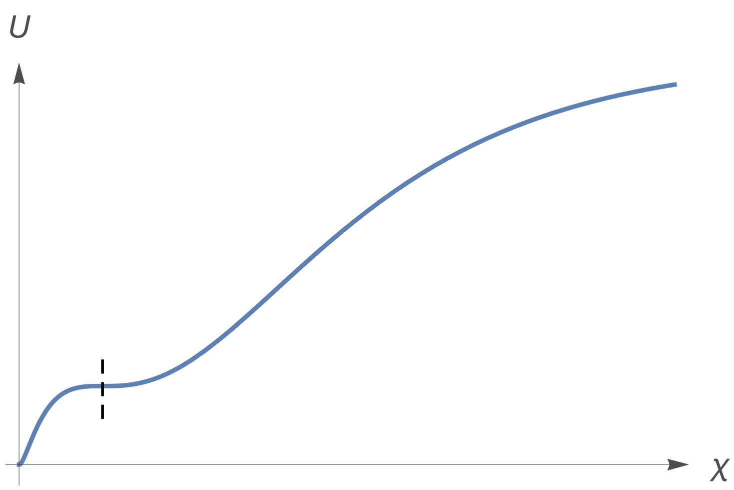
Loop-corrected potential



- 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: can give even smaller *r* than plateau.

A feature below the plateau

- We want to produce CMB perturbations on the plateau and have a slow-down feature at smaller field values.
- This can be generated by Standard Model loop corrections.



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Black hole dark matter

- Loop corrections can be used to produce dark matter from the Higgs. (SR and Tomberg: 1810.12608)
- This requires a feature in the potential that slows down the field, enhancing perturbations.
- Once the perturbations re-enter Hubble radius after inflation, they collapse into black holes (BHs).
- These then evaporate down to Planck-scale relics.
- The relic BHs can be all of the dark matter.