Inflation from the Higgs boson

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Motivations for inflation

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- CMB spectrum is observed to be quasi scale-invariant, it is well described by a Gaussian statistics and exhibits acoustic peaks in the angular power spectrum. These characteristics turn into requesting Gaussian, quasi scale-invariant and adiabatic initial conditions.

Inflaton and its properties

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Quantum fluctuations of the inflaton are free and massless scalar fields in a de Sitter universe: they obey a Gaussian statistics and thus solve also the second problem

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The Lagrangian

Consider Lagrangian of the SM non-minimally coupled to gravity,

$$L_{\text{tot}} = L_{\text{SM}} - \frac{M^2}{2} R - \xi H^\dagger H R \tag{1}$$

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- L_{SM} is the SM part
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The vantage of this model is that no new particle besides those already present in the electroweak theory is required.

Remark -1

This model is formally equivalent to R^2-inflation:

$$S_{R^2} = -\frac{M_P^2}{2} \int \mathrm{d}^4 x \sqrt{-g} \left(R - \frac{R^2}{6\mu} \right)$$

The difference in the predictions between the two models is of order 10^{-3} (F. Bezrukov and D. Gorbukov, arXiv:1111.4397v2).

Minimal coupling

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"Good" particle physics phenomenology but "bad" inflation: matter fluctuations way larger than those observed.

Induced gravity

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"Good" inflation but "bad" particle physics: Higgs field almost completely decoupled from the other fields of SM.

Scalar sector of the action of the SM non-minimally coupled to gravity (in unitary gauge $H = h/\sqrt{2}$):

$$S_J = \int \mathrm{d}^4x \sqrt{-g} \left\{ \frac{M^2 + \xi h^2}{2} R + \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{\lambda}{4}(h^2 - v^2)^2 \right\} \tag{2}$$

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Through a conformal transformation we can switch to the Einstein frame, where the action is

$$S_E = \int \mathrm{d}^4x\sqrt{-\hat{g}}\left\{-\frac{M_P^2}{2}\hat{R} + \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - U(\chi)\right\} \tag{3}$$

with

- $\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}$, $\Omega^2 = 1 + \xi h^2/M_P^2$
- χ is a scalar field which casts the kinetic term in minimal form, defined by

$$\frac{\mathrm{d}\chi}{\mathrm{d}h} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2/M_P^2}{\Omega^4}} \tag{4}$$

- $\hat{R}$ is the Ricci scalar calculated using the metric $\hat{g}_{\mu\nu}$
- The potential $U(\chi)$ is

$$U(\chi) = \frac{1}{\Omega(\chi)^4}\frac{\lambda}{4}(h(\chi)^2 - v^2)^2 \tag{5}$$

- $v \approx 246$ GeV is the vacuum expectation value of the Higgs field.

Potential

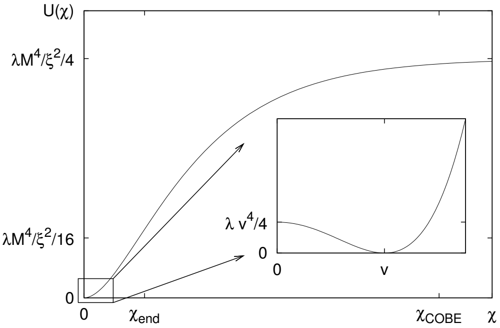

Figure: Effective potential in the Einstein frame.

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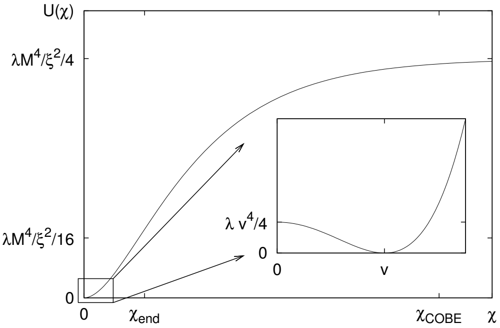

Figure: Effective potential in the Einstein frame.

For large values of the field $h \gg M_P/\sqrt{\xi}$ (or $\chi \gg \sqrt{6}M_P$) the potential is exponentially flat. This feature makes successful inflation possible.

Slow-roll parameters

In the limit $h^2 \gg M_P^2/\xi \gg v^2$,

$$\epsilon = \frac{M_P^2}{2}\left(\frac{\mathrm{d}U/\mathrm{d}\chi}{U}\right)^2 \simeq \frac{4M_P^4}{3\xi^2 h^4} \tag{6}$$

$$\eta = M_P^2 \frac{\mathrm{d}^2U/\mathrm{d}\chi^2}{U} \simeq -\frac{4M_P^2}{3\xi h^2} \tag{7}$$

At the end of the inflation $\epsilon \simeq 1$, so

$$h_{\text{end}} \simeq \left(\frac{4}{3}\right)^{1/4} \frac{M_P}{\sqrt{\xi}} \approx 1.07 \frac{M_P}{\sqrt{\xi}}$$

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The number of e-foldings for the change from h_0 to h_{end} is therefore

$$N = -\frac{1}{M_P} \int_{h_0}^{h_{\text{end}}} \frac{\mathrm{d}h}{\sqrt{2\epsilon(h)}} \simeq \frac{6}{8} \frac{h_0^2 - h_{\text{end}}^2}{M_P^2/\xi} \tag{8}$$

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Remark -2

For all $\sqrt{\xi} \lll 10^{17}$ the inflationary physics does not depend on the SM scale v.

For $N \simeq 60$ e-foldings of inflation, imposing the COBE normalization (D. Lyth and A. Riotto, arXiv:hep-ph/9807278v4) computed using Planck 2013 data (Planck collaboration, arXiv:1303.5082v2)

$$\frac{U}{\epsilon} = (0.027 M_P)^4$$

we find

$$\xi \simeq \sqrt{\frac{\lambda}{3}} \frac{N}{0.027^2} \simeq 47500\sqrt{\lambda} = 47500 \frac{m_H}{\sqrt{2}v} \approx 17190 \tag{9}$$

where we used the recent result $m_H = 125.9$ GeV (Particle Data Group, Phys.Rev. D86 (2012), 010001).

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where we used the recent result $m_H = 125.9$ GeV (Particle Data Group, Phys.Rev. D86 (2012), 010001).
The value of ξ found falls in the range assumed at the beginning, $1 \ll \sqrt{\xi} \ll 10^{17}$.

Predictions of the model

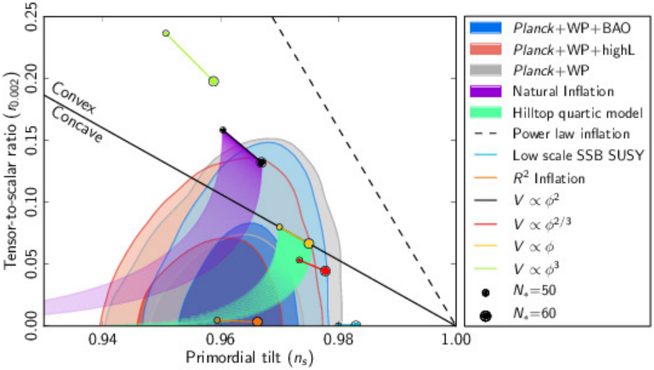
For $N = 60$ the spectral index $n = 1 - 6\epsilon + 2\eta$ and the tensor to scalar ratio $r = 16\epsilon$ are

$$n \simeq 1 - \frac{8(4N+9)}{(4N+3)^2} \simeq 0.97 \tag{10}$$

$$r \simeq \frac{192}{(4N+3)^2} \simeq 0.0033 \tag{11}$$

Predictions of the model -2

The predicted values fall within one sigma of the current Planck measurements (Planck collaboration, arXiv:1303.5082v2):



Radiative corrections

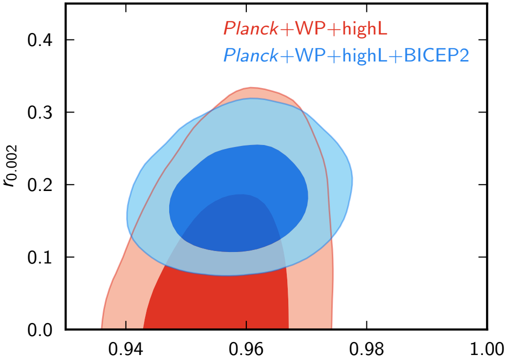
It is crucial that radiative corrections don't spoil the flatness of the potential at large χ in order to maintain inflation possible.

In order to achieve this, it is possible to show that at the inflationary stage the sufficient condition is the requirement of asymptotic symmetry of the theory at large values of the inflaton field (F. Bezrukov et al., arXiv:1008.5157v4):

- In the Jordan frame, the corresponding symmetry is scale invariance.
- In the Einstein frame, symmetry under shifts of the inflaton field.

A (dis)proof?

BICEP2 announced on March 2014 the detection of B-modes in the polarization of the CMB, consistent with inflation and gravitational waves in the early universe at the level of $r = 0.20^{+0.07}_{-0.05}$. (BICEP2 collaboration, arXiv:1403:3985v3)



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The attempts made to reconcile with BICEP2 are essentially of two types:

- Flatten the potential in some other ways (e.g. fine tuning the Higgs and top masses such that Higgs self-coupling $\lambda \sim 10^{-4}$ or adding new physics beyond SM which can affect the running of λ)

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- Achieve large r (e.g. tuning Higgs potential to form a false vacuum at large scales and adding a new scalar with non-minimal coupling to gravity)

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- Achieve large r

In both cases, the canonical HI with non-minimal coupling to gravity as the only new physical input doesn't appear to be compatible with BICEP2 result.