On the predictivity of single field inflationary models.

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Based on C.P. Burgess, S.P Patil, M. Trott, arXiv:1402.1476; JHEP 1406 (2014) 010

Inflationary cosmology in a nutshell

Inflation is a phase of primordial accelerated (almost 'exponential') expansion that generated the initial conditions for the big bang.

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- Does this make sense from the EFT perspective?

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Q.) We only see perturbations. How do we connect observables to underlying theory? A.) Start with the action of gravity + the inflaton:

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- $$S_{3,\mathcal{R}} = M_{pl}^2\int d^4x\Big[-\epsilon a\mathcal{R}(\partial\mathcal{R})^2 + 3\epsilon a^3\mathcal{R}\dot{\mathcal{R}}^2 - \epsilon a^3\frac{\dot{\mathcal{R}}^3}{H} - 2a^3\partial_i\theta\partial^2\theta\partial_i\mathcal{R} + \frac{a^3}{2}\left(3\mathcal{R} - \frac{\dot{\mathcal{R}}}{H}\right)(\partial_i\partial_j\theta\partial_i\partial_j\theta - \partial^2\theta\partial^2\theta)\Big]$$
- $\partial^2\theta = -\frac{\partial^2\mathcal{R}}{a^2H} + \epsilon\dot{\mathcal{R}}$

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- $\partial^2\theta = -\frac{\partial^2\mathcal{R}}{a^2H} + \epsilon\dot{\mathcal{R}}$
- $\mathcal{R}$ is conserved on super-horizon scales. Want to calculate n-point correlation functions and compare with observations.

The in-in formalism in one slide

We are interested in computing the late (finite) time correlator $|k_1|^3\langle\mathcal{R}_{\vec{k}_1}(\tau)\mathcal{R}_{\vec{k}_2}(\tau)\rangle := 2\pi^2\delta^3(\vec{k}_1+\vec{k}_2)\mathcal{P}_\mathcal{R}$, and similarly for γ_{ij} .

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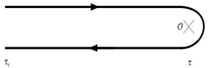
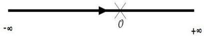
- Dyson operator: $U(\tau,\tau_0) = T\exp\left(-i\int_{\tau_0}^{\tau}H_I(\tau')d\tau'\right)$
- Denoting $\bar{T}$ as anti time ordering–
  $\langle\mathcal{O}(\tau)\rangle = \langle 0_{in}|\bar{T}\left[\exp\left(i\int_{\tau_0}^{\tau}H_I(\tau')d\tau'\right)\right]\mathcal{O}(\tau)\,T\left[\exp\left(-i\int_{\tau_0}^{\tau}H_I(\tau')d\tau'\right)\right]|0_{in}\rangle$
- Equivalently:
  $\langle\mathcal{O}(\tau)\rangle = \langle 0_{in}|T_C\left[\exp\left(-i\oint H_I(\tau')d\tau'\right)\mathcal{O}(\tau)\right]|0_{in}\rangle$





where we have to distinguish fields on the different contours.

- Or equivalently in terms of the original operator basis:
  $\langle\mathcal{O}(\tau)\rangle = \sum_{n=0}^{\infty} i^n\int_{\tau_0}^{\tau}d\tau_n\int_{\tau_0}^{\tau_n}d\tau_{n-1}\ldots\int_{\tau_0}^{\tau_2}d\tau_1\langle[H_I(\tau_1),[H_I(\tau_2),\ldots[H_I(\tau_n),\mathcal{O}(\tau)]\ldots]]\rangle$

Predictions

Given a background that is close enough to dS:

- that is, with $\epsilon = \frac{\dot\phi_0^2}{2M_{\rm pl}^2 H^2} \equiv -\dot H/H^2 \ll 1$
- The mode functions each Fourier mode of $\mathcal{R}$ are given by:

$$\mathcal{R}_k(\tau) = \frac{e^{i\left(\nu+\frac{1}{2}\right)\frac{\pi}{2}}}{2}\sqrt{\frac{\pi}{2\epsilon}}\frac{[H(1-\epsilon)]^{\nu-1/2}}{M_{\rm pl}}(-\tau)^{\nu}H_\nu^{(1)}(-k\tau); \quad \nu := \frac{3-\epsilon}{2(1-\epsilon)}$$

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- Observed spectrum
  $\mathcal{P}_{\mathcal{R}} = \frac{H^2(k)}{8\pi^2 M_{pl}^2\epsilon} \simeq 2\times 10^{-9} \to H \simeq 10^{15}\epsilon^{1/2}GeV; V^{1/4} \simeq 10^{16}\epsilon^{1/4}GeV$
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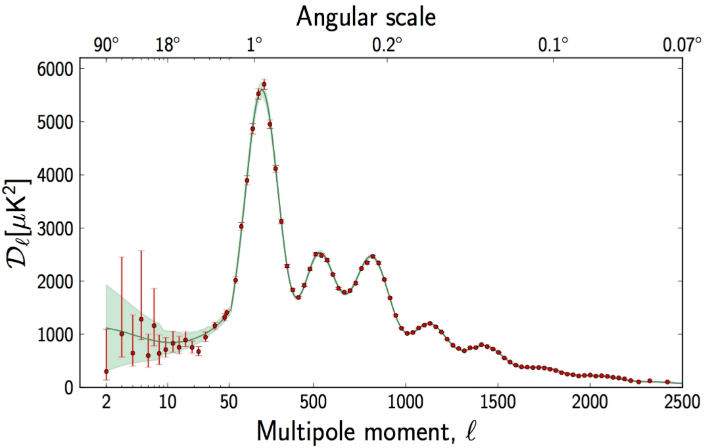
- Can show (Lyth bound) that $\Delta\phi_{\surd} \geq \mathcal{N} M_{pl}\sqrt{r}$ ...
- Attn: string theorists: are you OK with this?

What we see:


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

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- $\Omega_b h^2 = 0.02207 \pm 0.00033$ $\quad n_s = 0.9616 \pm 0.0094$
  $\Omega_c h^2 = 0.1196 \pm 0.0031$ $\quad ln\,(10^{10} A_s) = 3.103 \pm 0.072$
  $\theta_{MC} = 0.00104 \pm 0.00068$ $\quad \tau = 0.097 \pm 0.038$
  PLANCK XVI, arXiv:1502.01589

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- $\exists$ a *single* effectively light degree of freedom at $\sim \epsilon^{1/4} 10^{16} GeV^*$. Observable tensors $\to 10^{16} GeV$?
  - whose field modes began in the relevant vacuum state (BD)
  - whose self interactions and interactions with other fields are sufficiently weak or irrelevant *throughout* inflation
  - which couples strongly enough to the standard model so that efficient (pre)heating occurs...* Antoniadis, Patil arXiv:1410.8845

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How does these requirements sit with our understanding of Effective field theory? Obtaining *enough* inflation requires field excursions.

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- By thinking about this problem honestly, can rule out a lot of models a priori.

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- Not predictive $\leftrightarrow$ need to know UV conmpletion.

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- $\frac{\mathcal{L}_J}{\sqrt{-\hat{g}}} = \mathcal{L}_{SM} - \left[\frac{M_{pl}^2}{2} + \xi\left(H^\dagger H\right)\right]\hat{R} + \cdots$

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- N.B. kinetic mixing of the radial mode (singlet) and the Goldstone modes! – crucially distinction between Higgs inflation and singlet scalar field w/ quartic potential.

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- For ~ 58 efolds, $n_s \simeq 0.967, r \simeq 0.0031$

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- $\Lambda_{int} \simeq 4\pi\bar{\phi}$ characteristic of all models with un-Higgsed vectors (from longitudinal gauge boson scattering).

  c.f. review by Contino 2010

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- 'Threshold' effects could affect your observables if you want to connect to low energy EW physics (one of the major attractions of Higgs Inflation).

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- Discovery of the Higgs 2012 → have to take SM parameters up to three sigma away from their central values to obtain positive quartic coupling at $M_{pl}/\sqrt{\xi}$.

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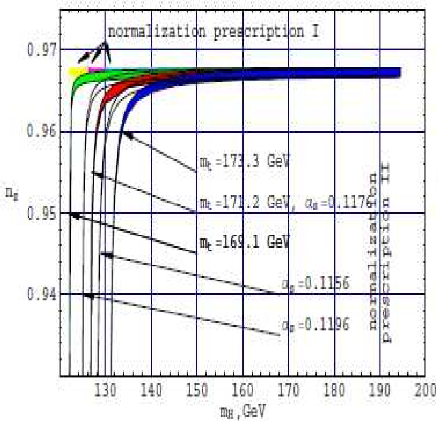

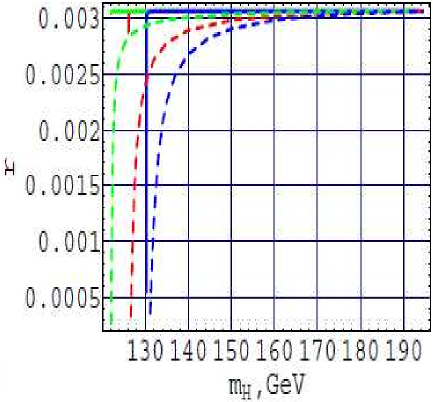

- From Bezrukov 2013.

Running up to inflation

In order to implement the running honestly, had to run up from the SM parameters at top mass (computed at 2 loops to NNLO):

Buttazzo, Degrassi, Giardino, Giudice, Salvio, Strumia 2013

- $\lambda(m_t) = 0.12711, y_t(m_t) = 0.93558, g'(m_t) = 0.35761,$
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- Compute effective potential during inflation, CMB observables determined from COBE normalization and fixing the number of e-folds.
- But what about the fact that $\Lambda_{int} \simeq 4\pi\bar{\phi}$ during inflation? Threshold effects at M_{pl}/ξ ?

Higgs effective inflation

Higgs inflation is not renormalizable. Obliged to treat it as an effective description. D=6 SM operators mix into the running of SM parameters under RGE, even at one loop. Jenkins, Manohar, Trott 2013

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- Wilson coefficients affect the running substantially. Unless we know the UV completion (i.e. can specify all the coefficients), have to allow for them to represent a *theoretical uncertainty* in the predictions of Higgs inflation.

Higgs effective inflation

Can repeat the analysis done by others allowing for the theoretical uncertainty represented by these unknown Wilson coefficients, and compute the effects on CMB observables. C.P.Burgess, S.P.Patil, M.Trott, arXiv:1402.1476

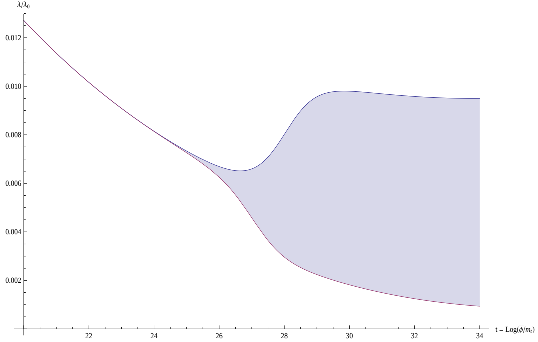


Figure: The effect of the unknown UV completion on the running of the quartic coupling in the Higgs inflation scenario.

Higgs effective inflation

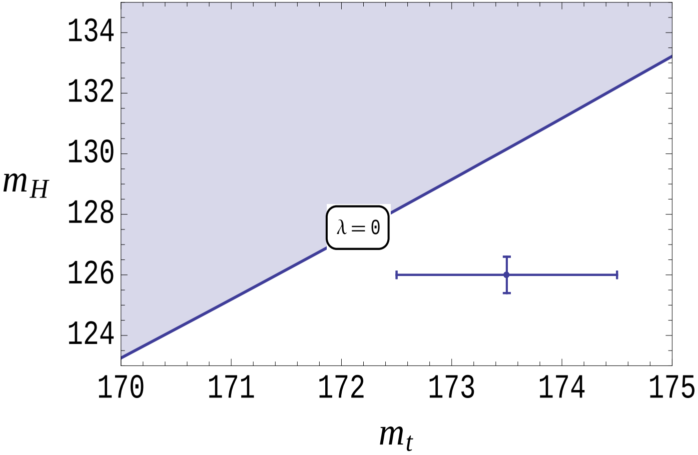


Figure: Initial conditions that separate $\lambda < 0$ from $\lambda > 0$ at $M_{pl}/\sqrt{\xi}$

Higgs effective inflation

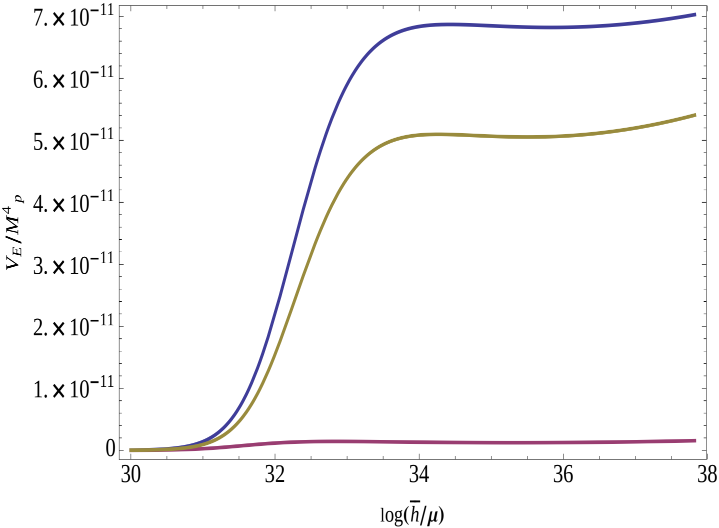
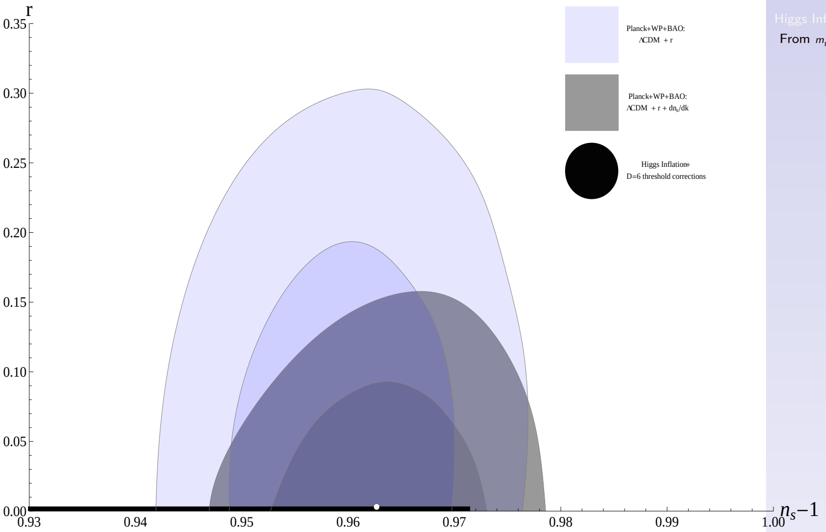


Figure: Effective potential over the range of Wilson coefficients

Higgs effective inflation



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- A related question to predictivity– is inflation falsifiable?