Higgs Inflation and Other Stories

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PHY

Me

- Studies in Helsinki: theoretical physics, mathematics
- PhD November 2019: ‘Cosmology with Higgs inflation’
- Supervisors: Syksy Räsänen, Kari Enqvist
- Other collaborators: Javier Rubio, Vera-Maria Enckell, Daniel Figueroa, Sami Raatikainen, Tommi Tenkanen
- Keywords: Cosmic inflation, reheating, Higgs inflation, PBHs, Palatini formulation of GR

Cosmology with Higgs inflation

- **Higgs inflation at the hilltop**
  V.-M. Enckell, K. Enqvist, S. Räsänen and E. Tomberg, [arXiv:1802.09299]
- **Planck scale black hole dark matter from Higgs inflation**
  S. Räsänen and E. Tomberg, [arXiv:1810.12608]
- **Preheating in Palatini Higgs inflation**
  J. Rubio and E. Tomberg, [arXiv:1902.10148]

Higgs inflation

- Cosmic inflation: explains homogeneity, isotropy, flatness of the universe; predicts CMB anisotropies
- Higgs inflation: simple model; SM Higgs is the inflaton, no new fields beyond the SM
  - Only non-minimal coupling to gravity ξ needs to be added

Higgs inflation

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{2}\left(M^2 + \xi h^2\right)R + \frac{1}{2}g^{\mu\nu}\partial_\mu h\partial_\nu h - \frac{\lambda}{4}h^4\right]$$

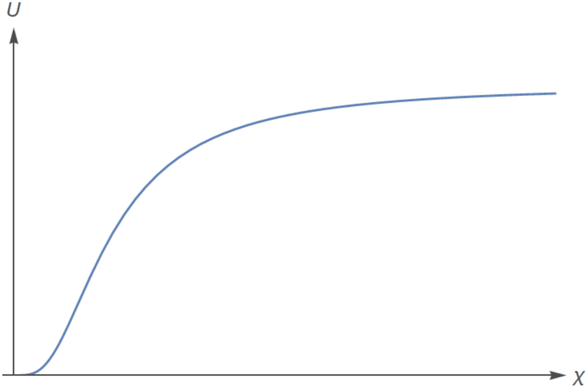
- First studied for SM Higgs in [0710.3755]
- Standard procedure: Weyl transformation

$$g_{E\mu\nu} = g_{\mu\nu}\left(1 + \frac{\xi h^2}{M^2}\right), \quad \frac{dh}{d\chi} = \frac{1 + \xi h^2}{\sqrt{1 + \xi h^2 + 6\xi^2 h^2}}$$

$$S_E = \int d^4x\sqrt{-g_E}\left[-\frac{1}{2}M^2 R_E + \frac{1}{2}g_{E\mu\nu}\partial^\mu\chi\partial^\nu\chi - U(\chi)\right]$$

Higgs inflation

- Einstein frame potential:



$$V = \frac{\lambda}{4} F^4[h(\chi)] \, , \qquad F(h) \equiv \frac{h}{\sqrt{1 + \xi h^2}} \approx \frac{1}{\sqrt{\xi}} \left(1 - e^{-\sqrt{2/3}\chi} \right)^{1/2}$$

Higgs inflation

- CMB predictions fit the observations:

$$A_s = \frac{\lambda N^2}{72\pi^2\xi^2}\,,$$
$$n_s = 1 - \frac{2}{N}\,, \quad r = \frac{12}{N^2}$$

- For $N \sim 50$, $\xi = 800\sqrt{\lambda}N$:

$$n_s \approx 0.96\,, \quad r \approx 4.8 \times 10^{-3}$$

Quantum corrections

- Add loop corrections:

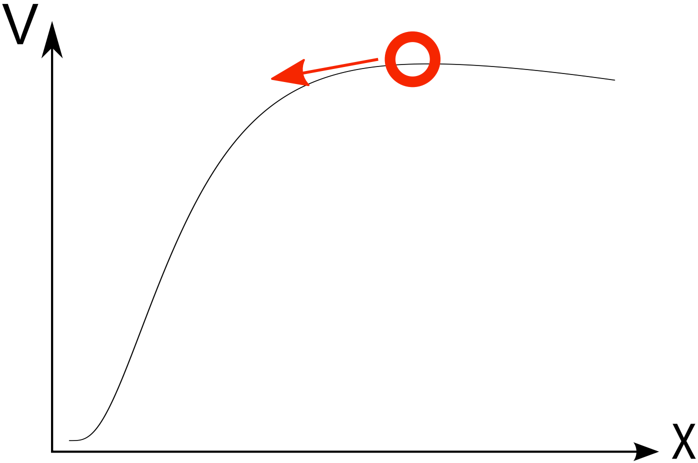
$$V_{1-\mathrm{loop}}(\phi) \sim m^4(\phi) \ln \frac{m^2(\phi)}{\mu^2}$$

- Run the couplings to μ value that makes the corrections small:

$$\frac{d\alpha}{d \ln \mu} = \beta$$

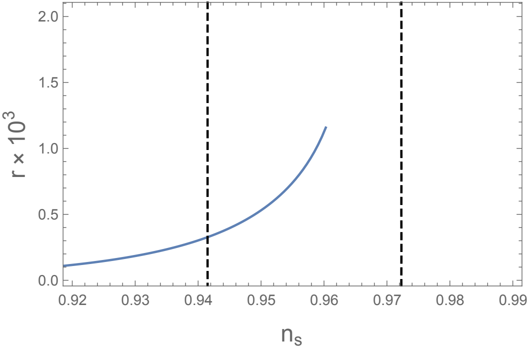
- Use effective field theory; connection to EW scale physics not fully determined

Special case: Hilltop



Hilltop inflation

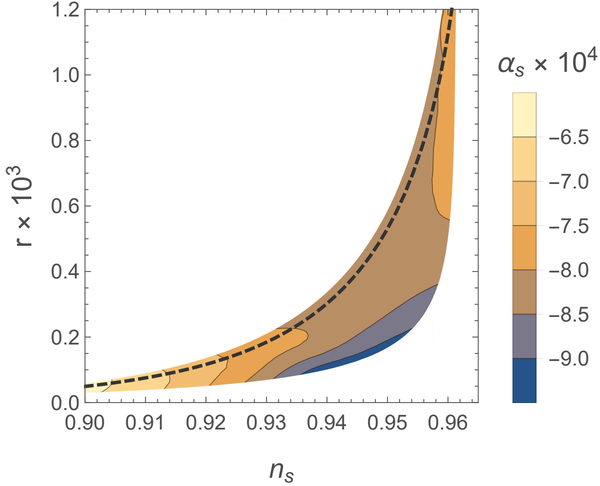
- Analytical approximation: predictions



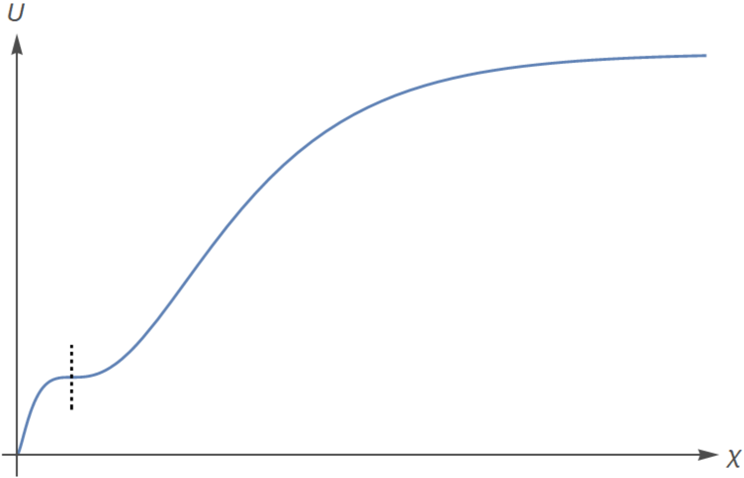
- Note: $r < \frac{3}{N^2}$, smaller by at least a factor of four compared to tree level result

Hilltop inflation

- Numerical scan:



Special case: Critical point

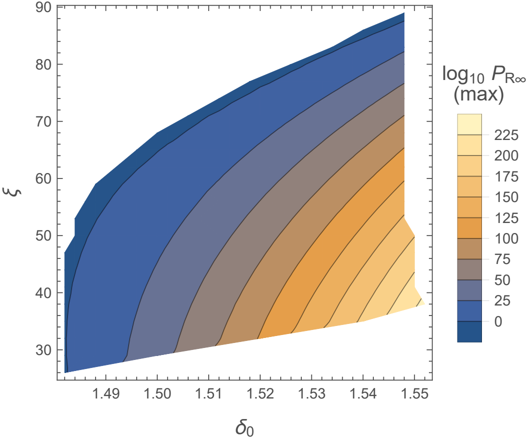


Critical point inflation

- Critical point: enhanced perturbations
- Chance for production of primordial black holes (PBH)
  - Dark matter?
- Slow-roll approximation breaks down; need to calculate numerically

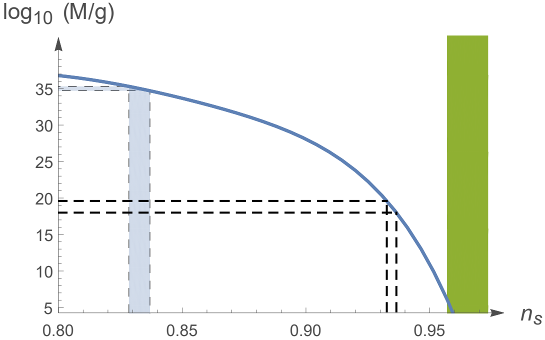
Critical point inflation

- Numerical scan: [1810.12608]



- Efficient PBH production!

Critical point inflation



- Problem: need $M < 10^6$ g
- Evaporation by Hawking radiation!
- Planck mass relics?

Palatini formulation of GR

- General relativity degrees of freedom: metric $g_{\mu\nu}$ and connection $\Gamma^{\alpha}_{\beta\gamma}$
- Usually, $\Gamma^{\alpha}_{\beta\gamma}$ written in terms of $g_{\mu\nu}$ (Levi-Civita connection; 'metric formulation of GR')
- Alternatively, may take $\Gamma^{\alpha}_{\beta\gamma}$ and $g_{\mu\nu}$ to be independent ('Palatini formulation')
  - Often equivalent to metric case
  - NOT with a non-minimal coupling to gravity!

Higgs inflation: metric vs. Palatini

- Metric: [0710.3755]

$$\xi \approx 800\sqrt{\lambda}N \sim 10^4 \quad (N = 50, \lambda \sim 0.1)$$

$$n_s \approx 1 - \frac{2}{N} \approx 0.96\,, \quad r \approx \frac{12}{N^2} \approx 4.8 \times 10^{-3}$$

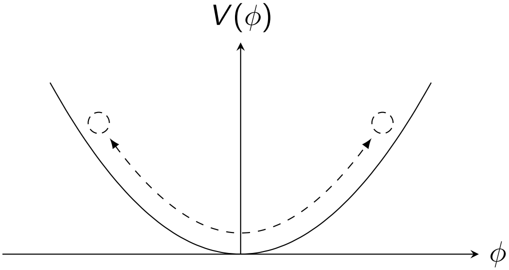
- Palatini: [0803.2664]

$$\xi \approx 3.8 \times 10^6 \lambda N^2 \sim 10^9$$

$$n_s \approx 1 - \frac{2}{N} \approx 0.96\,, \quad r \approx \frac{2}{\xi N^2} \sim 10^{-12}$$

Reheating

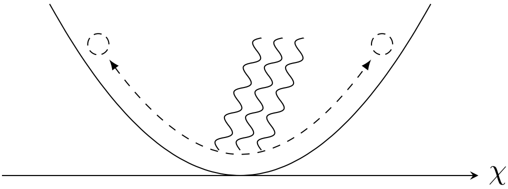
- After inflation, inflaton oscillates around its minimum



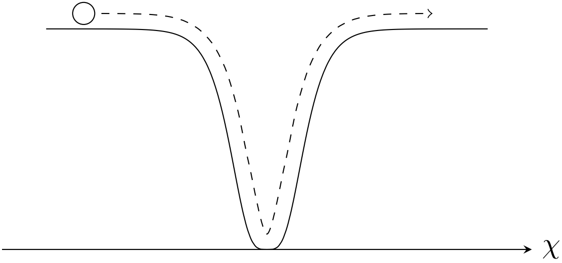
$$\ddot{\chi} + \underbrace{3H\dot{\chi}}_{\text{friction}} + \underbrace{V'(\chi)}_{\text{oscillation}} = 0$$

Reheating

- Need to transfer energy density into radiation
- Many channels
  - Perturbative decays
  - Non-perturbative processes (‘preheating’)



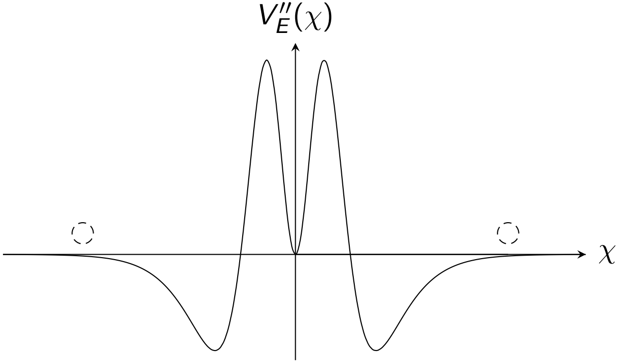
Higgs preheating: Palatini case



- Oscillation amplitude stays almost constant!

Higgs preheating: Palatini case

- Near the pleateau: $m_h^2 = V_E''$ is negative $\Rightarrow$ tachyonic particle production



- Rapid (p)reheating in just a few oscillations

Other projects

- Initial conditions for plateau inflation [2002.02420]
- Quantum corrections to Higgs inflation in Palatini formulation
- Numerical stochastic inflation and PBH formation

Interests

- Cosmic inflation
- PBHs
- Applications of QFT
- Quantum phenomena in cosmology, decoherence
- (Early universe) (theoretical) cosmology
- . . .

Thank you!

Quantum corrections: "Recipe"

- Potential: $V = V_{tree} + V_{1-\mathrm{loop}}$,

$$V_{1-\mathrm{loop}} = \frac{6m_W^4}{64\pi^2}\left(\ln\frac{m_W^2}{\mu^2} - \frac{5}{6}\right) + \frac{3m_Z^4}{64\pi^2}\left(\ln\frac{m_Z^2}{\mu^2} - \frac{5}{6}\right) - \frac{3m_t^4}{16\pi^2}\left(\ln\frac{m_t^2}{\mu^2} - \frac{3}{2}\right),$$

$$m_W^2 = \frac{g^2F^2}{4}, \qquad m_Z^2 = \frac{(g^2 + g'^2)F^2}{4}, \qquad m_t^2 = \frac{y_t^2F^2}{2},$$

Quantum corrections: "Recipe"

- Running:

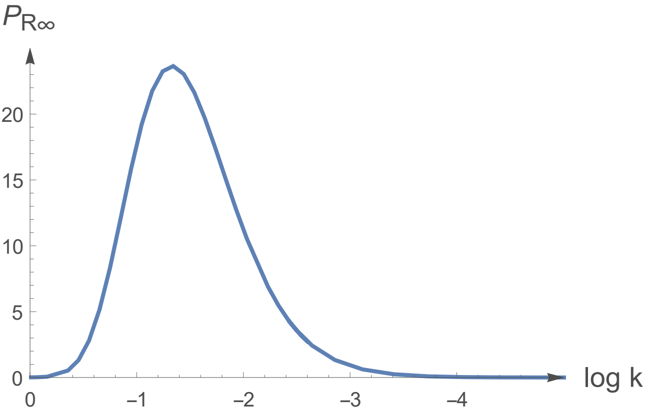
$$16\pi^2\beta_\lambda = -6y_t^4 + \frac{3}{8}\left(2g^4 + \left[g^2 + g'^2\right]^2\right),$$

$$16\pi^2\beta_{y_t} = y_t\left(\frac{9}{2}y_t^2 - \frac{9}{4}g^2 - \frac{17}{12}g'^2 - 8g_s^2\right),$$

$$16\pi^2\beta_g = -\frac{19}{6}g^3, \quad 16\pi^2\beta_{g'} = \frac{41}{6}g'^3, \quad 16\pi^2\beta_{g_s} = -7g_s^3$$

- Renormalization scale $\mu \sim \gamma F$

PBH numerics



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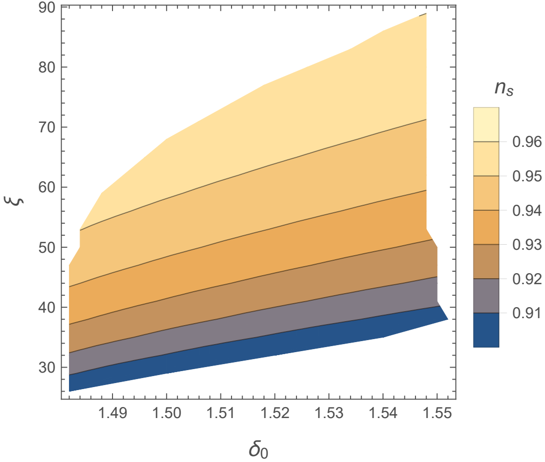
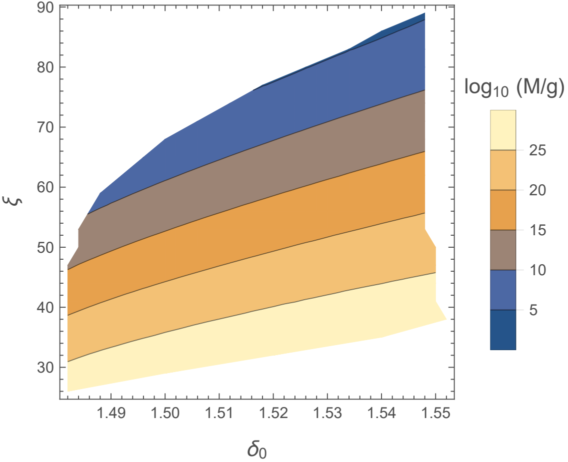


PBH numerics



PBH numerics