Criticality and Primordial Black Holes in Higgs-R^2 Inflation

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We investigate the Higgs near-criticality and its phenomenological consequences in the Higgs-R^2 inflation setup, specifically focusing on primordial black hole production. This specific inflationary model consists of both the Higgs field with non-minimal coupling and the R^2 term, leading to a multifield scenario. By imposing running of the Higgs self coupling to near-criticality, an inflection point forms in the tangential direction of the field evolution. This in turn leads to an enhanced curvature power spectrum, which sources primordial black hole production. Our results indicate that this scenario can produce O(10-17)-O(10-16) M☉, which is an allowed region for a significant contribution to dark matter, while remaining consistent with Planck 2018 cosmic microwave background observables.

1 Higgs-R^2 Inflation

$$S=\int d^4x\sqrt{-g_J}\left[\frac{M_P^2}{2}\left(R_J+\frac{\xi h^2}{M_P^2}R_J+\frac{R_J^2}{6M^2}\right)-\frac{1}{2}g^{\mu\nu}\nabla_\mu h\nabla_\nu h-\frac{\lambda_{\rm eff}}{4}h^4\right]$$

non minimal coupling — R^2 term — Higgs effective potential

Through frame redefinition, the Einstein action becomes

$$S_E=\int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R-\frac{1}{2}g^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi-\frac{1}{2}e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_P}}g^{\mu\nu}\nabla_\mu h\nabla_\nu h-U(\phi,h)\right]$$

$$U(\phi,h)\equiv e^{-2\sqrt{\frac{2}{3}}\frac{\phi}{M_P}}\left\{\frac{3}{4}M_P^2M^2\left(e^{\sqrt{\frac{2}{3}}\frac{\phi}{M_P}}-1-\frac{\xi h^2}{M_P^2}\right)^2+\frac{\lambda_{\rm eff}}{4}h^4\right\}$$

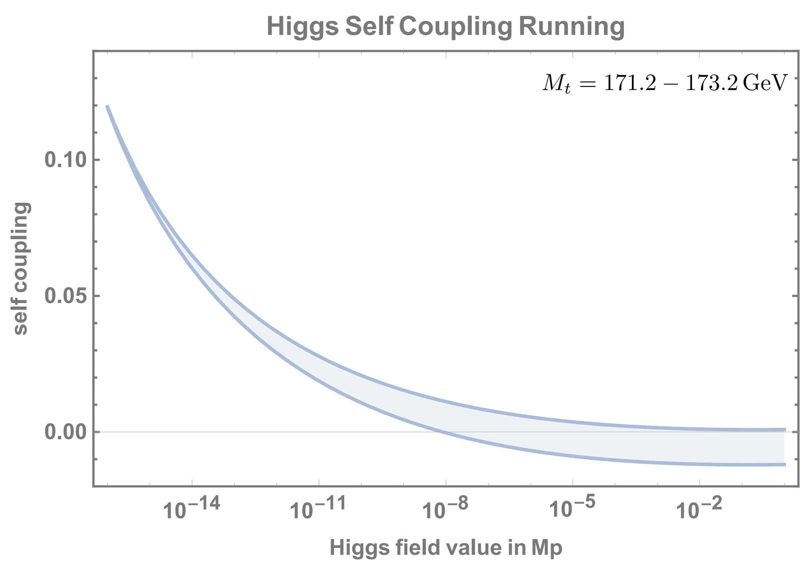
Quantum level generalization of both Starobinsky and Higgs inflation!

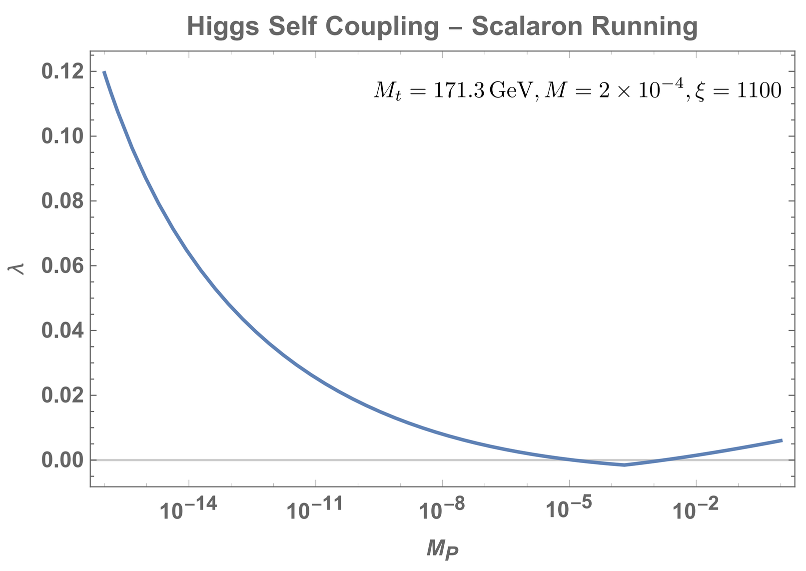
2 Self Coupling Running and Criticality - Scalaron effect

Current LHC data possess the possibility of near criticality, namely forming a minimum at 10^{17} - 10^{18} GeV.

Additional running from R^2 at the scalaron mass threshold is present, yet for parameters corresponding to successful inflation and near criticality the additional β-function contribution is subdominant. We approximate $\lambda_{\rm eff}$ around its minimum.

$$\lambda_{\rm eff}(h)=\lambda_m+b_\lambda\ln\left(\frac{h}{h_{\rm min}}\right)^2\qquad \delta\beta_\lambda=\frac{1}{16\pi^2}\frac{2\xi^2(1+6\xi)^2}{M_P^4}M^4$$





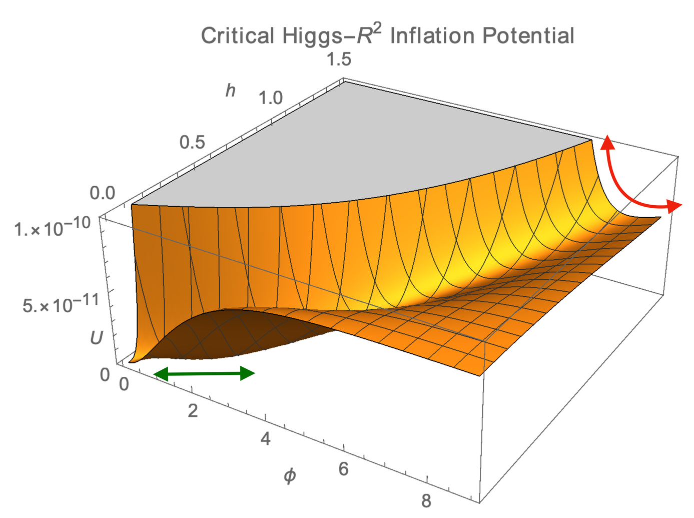
3 Critical Higgs-R^2 Inflation

By taking λ running into account in the Higgs-R^2 action, we obtain the Einstein potential.

$$U(\phi,h)\equiv e^{-2\sqrt{\frac{2}{3}}\frac{\phi}{M_P}}\left\{\frac{3}{4}M_P^2M^2\left(e^{\sqrt{\frac{2}{3}}\frac{\phi}{M_P}}-1-\frac{\xi h^2}{M_P^2}\right)^2+\frac{\lambda_m+b_\lambda\ln\left(\frac{h}{h_{\rm min}}\right)^2}{4}h^4\right\}$$

Benchmark Parameters :

$M=10^{-5}M_P,\ \xi=101,\lambda_m=2.394\times10^{-7},b_\lambda=1.24\times10^{-6},h_{\rm min}=0.1298\,M_P$

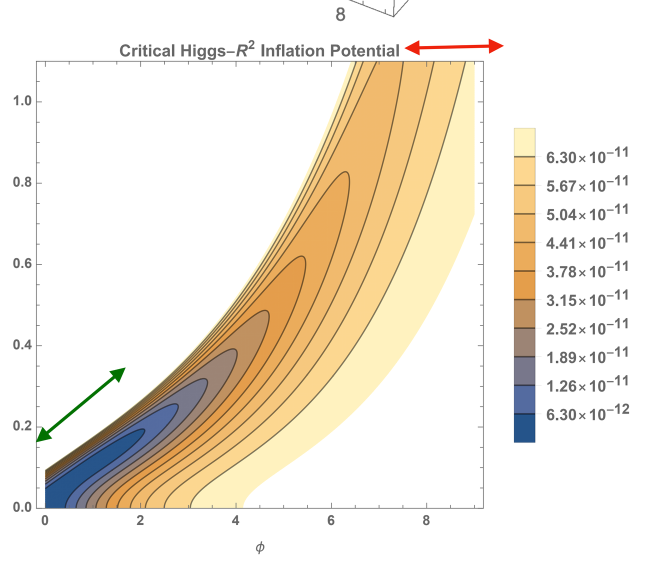


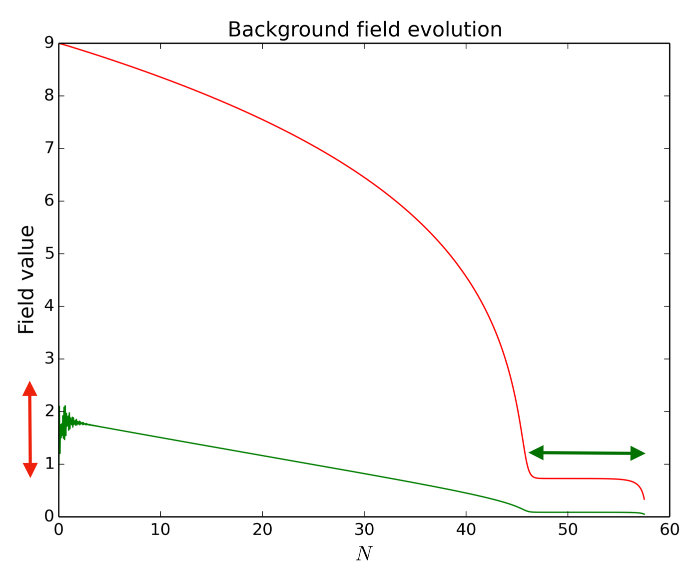
- Valley structure, quasi-single-field inflation
- Inflection point in the tangential direction, USR

$\frac{U(\phi_{\rm CMB})}{U(\phi_{\rm PBH})}\approx 10\qquad \Delta N_e\approx 10$ e-folds

Simple SR analysis fails ⟶ USR crucial in $P_R(k_{\rm PBH})$

$\epsilon\lll 1, |\eta|>1$





4 Physical Observables - Multi field inflation

Conventional slow-roll limit physical observables are not reliable. Although the inflation follows the valley, making its isocurvature sourcing negligible, USR effects are dominant in large k values.

δN formalism takes all effects into account when computing physical observables, specifically the comoving curvature power spectrum.

$$P_{\mathcal{R}}(k)=\frac{k^3}{2\pi^2}\frac{\partial N}{\partial\varphi^I}\frac{\partial N}{\partial\varphi^J}\langle\delta\varphi^I\delta\varphi^J\rangle\Big|_{k=aH}$$

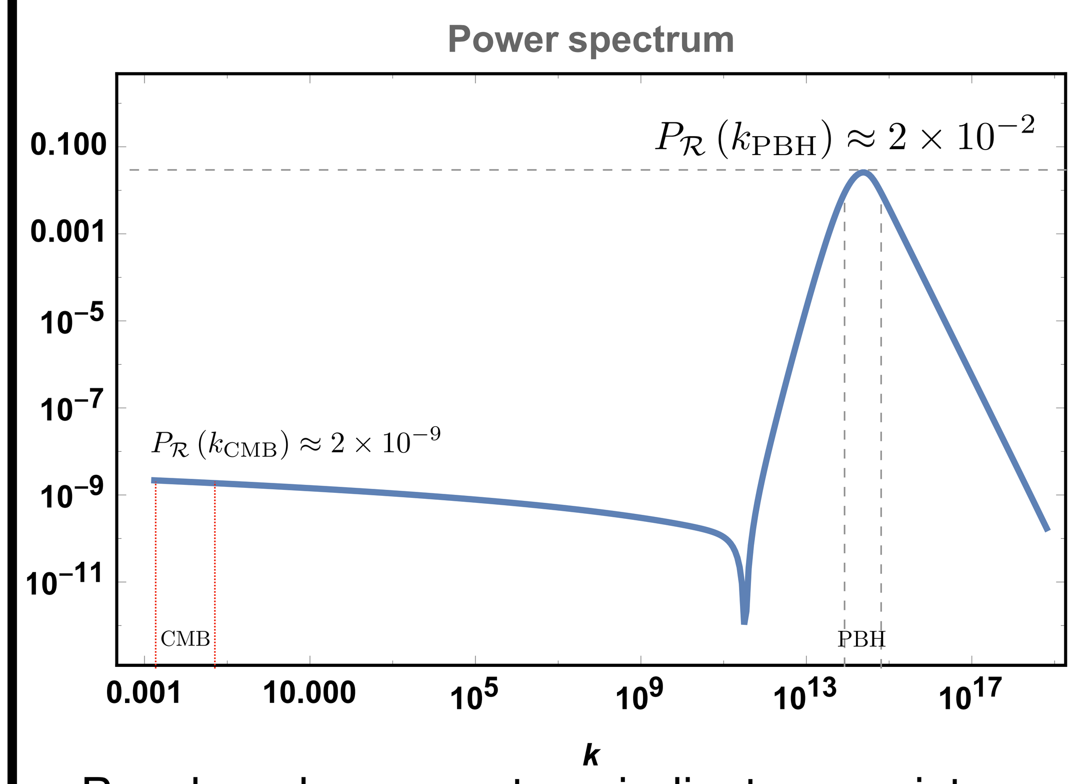
Due to the USR stage and nontrivial field space metric, it is unreasonable to compute physical observables analytically.

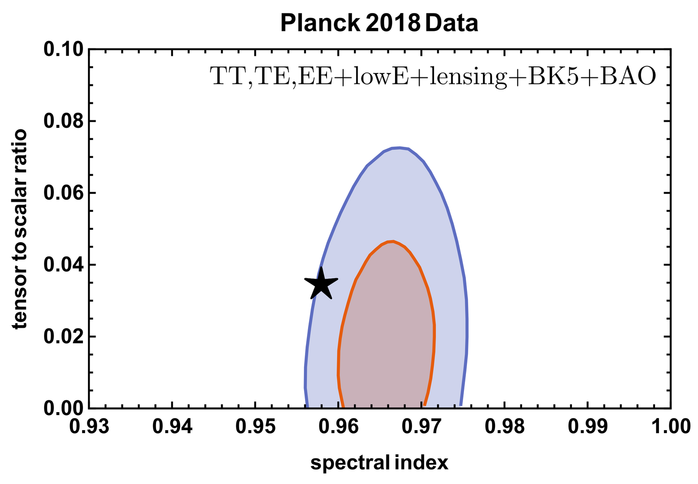
Basically evaluate each point with each individual initial condition in order to obtain the full spectrum of observables. Hence $2N$ solutions with $2N$ initial conditions $\{\varphi_I,\dot\varphi_I\}$.

$$\mathcal{D}_N\langle X^aX^b\rangle=\langle(\mathcal{D}_NX^a)X^b\rangle+\langle X^a(\mathcal{D}_NX^b)\rangle$$

⟶ Transport Method

5 Results





$$n_s=0.958\,,\quad r=0.0349$$

$$\frac{P_{\mathcal{R}}(k_{\rm PBH})}{P_{\mathcal{R}}(k_{\rm CMB})}\approx 10^7$$

Benchmark parameters indicate consistency with Planck, with a higher r compared to standard Higgs or R^2 inflation, which is expected to be in the range of future CMB experiments (BICEP3, CMB-S4, etc.).

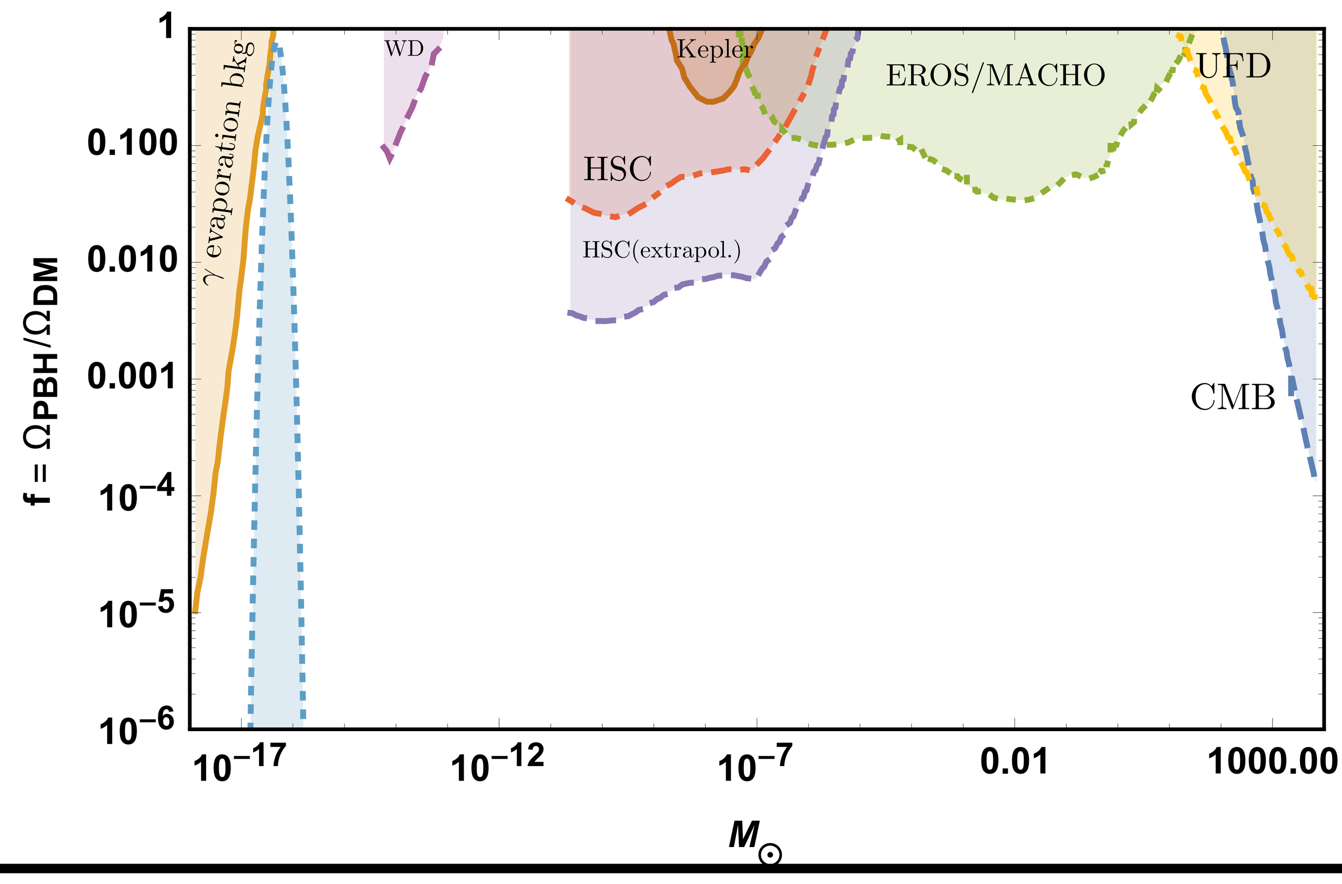
Power spectrum peaks at the range $k=\mathcal{O}(10^{14})-\mathcal{O}(10^{15})$.

Primordial black hole mass and abundance are calculated using peaks theory.

$$n_{\rm Peaks}(\nu_c,R)=\frac{1}{(2\pi)^2}\left(\frac{\langle k^2\rangle(R)}{3}\right)^{3/2}(\nu_c^2-1)\exp\left(-\frac{\nu_c^2}{2}\right)\qquad \beta_{\rm peaks}=n_{\rm peaks}M(R)/\rho=n_{\rm peaks}(2\pi)^{3/2}R^3$$

$$M_{\rm PBH}=\gamma\frac{1}{2G}H^{-1}_{\rm form}\approx 30M_\odot\left(\frac{\gamma}{0.2}\right)\left(\frac{g_{*,\rm form}}{10.75}\right)^{-1/6}\left(\frac{k}{2.9\times10^{-5}{\rm Mpc}^{-1}}\right)^{-2}\quad f_{\rm PBH}(M)=2.7\times10^8\left(\frac{\gamma}{0.2}\right)^{1/2}\left(\frac{g_{*,\rm form}}{10.75}\right)^{-1/4}\left(\frac{M}{M_\odot}\right)^{-1/2}\beta(M)$$

$$\nu_c=\delta_c/\sigma\qquad \delta_c=0.43$$



6 Conclusions and Discussions

- Higgs-R^2 inflation, shows a quasi single field inflation behavior.
- By imposing criticality, we obtain an inflection-point-like USR region.
- Through δN calculation of observables, we obtain an enhanced power spectrum consistent with CMB, along with $\mathcal{O}(10^{-17})-\mathcal{O}(10^{-16})\,M_\odot$ primordial black holes that can consist most of dark matter.
- A full parameter scan for allowed inflection point potential regions is a task remaining.

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