Inflation and singlet scalar dark matter

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Introduction

- The existence of non-baryonic dark matter requires additional degrees of freedom to be added to those of the Standard Model.

- The success of the inflationary model of cosmology in explaining the CMB data density perturbations generally results in the inclusion of an independent inflaton degree of freedom to the above extended Standard Model.

- However, a minimal extended Standard Model can be achieved with the identification of the Higgs field as not only setting the scale of the electroweak phase transition but also as the inflaton providing the large energy density and slow roll inflation in the cosmological state.

- This is realized by a large non-minimal coupling of the Higgs doublet to the gravitational Riemann scalar curvature with a coupling constant of the order 10^3 -10^4.

- The Higgs-inflaton effective potential in the inflationary region depends on radiative corrections in such a way as to provide a range of cosmologically acceptable values for the Higgs mass.

- We include the quantum effects of **dark matter** to the Higgs inflaton effective potential. The dark matter is described by a real scalar field that is a complete Standard Model gauge singlet.

The Standard Model plus Singlet Scalar

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_S}{4} S^4 - \kappa S^2 (H^\dagger H - \frac{v^2}{2})$$

- Minimalist model for non-baryonic dark matter.
- Singlet scalar is stable through a discrete symmetry.
- Only three additional parameters.
- Potential invisible decay of the Higgs boson into singlet scalars.

Stability of scalar potential:

$$\lambda, \lambda_S > 0$$

$$\lambda \lambda_S > \kappa^2 \;\; \text{for} \;\; \kappa < 0$$

Triviality and stability bounds

Renormalization group equations for scalar couplings:

$$(4\pi)^2\frac{d\bar\lambda}{dt} = 24\bar\lambda^2 - 6\bar{y}_t{}^4 + \frac{3}{8}\Big(2\bar{g}^4 + (\bar{g}'^2 + \bar{g}^2)^2\Big) + 12\bar{y}_t{}^2\bar\lambda - 3\bar{g}'^2\bar\lambda - 9\bar{g}^2\bar\lambda + 2\bar\kappa^2$$

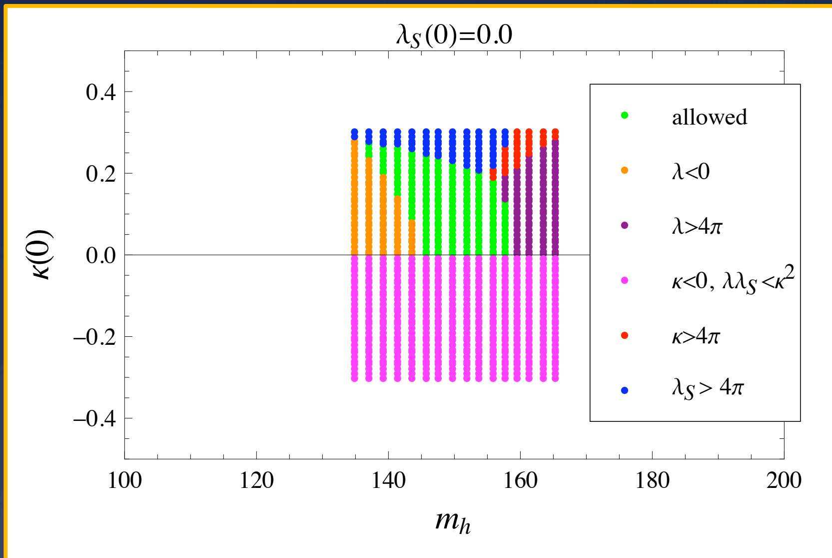
$$(4\pi)^2\frac{d\bar\kappa}{dt} = \bar\kappa\Big(8\bar\kappa + 12\bar\lambda + 6\bar\lambda_S + 6\bar{y}_t{}^2 - \frac{3}{2}\bar{g}'^2 - \frac{9}{2}\bar{g}^2\Big)$$

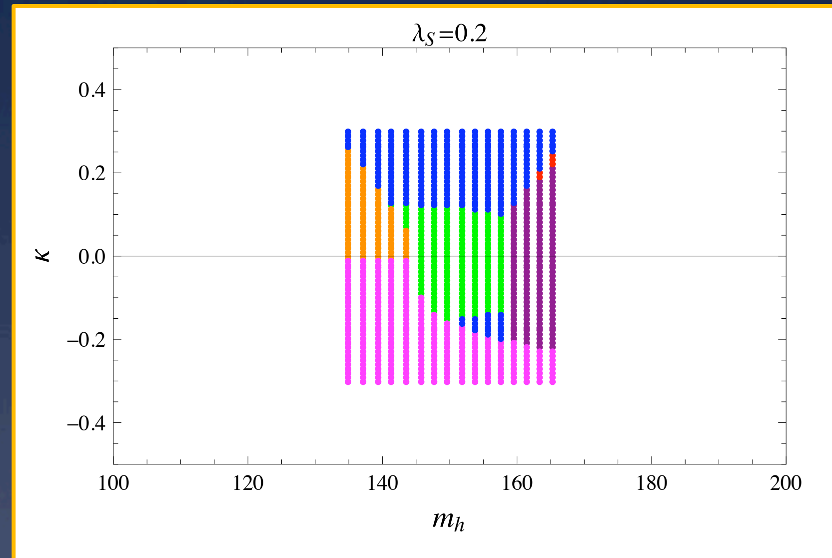
$$(4\pi)^2\frac{d\bar\lambda_S}{dt} = 18\bar\lambda_S^2 + 8\bar\kappa^2$$

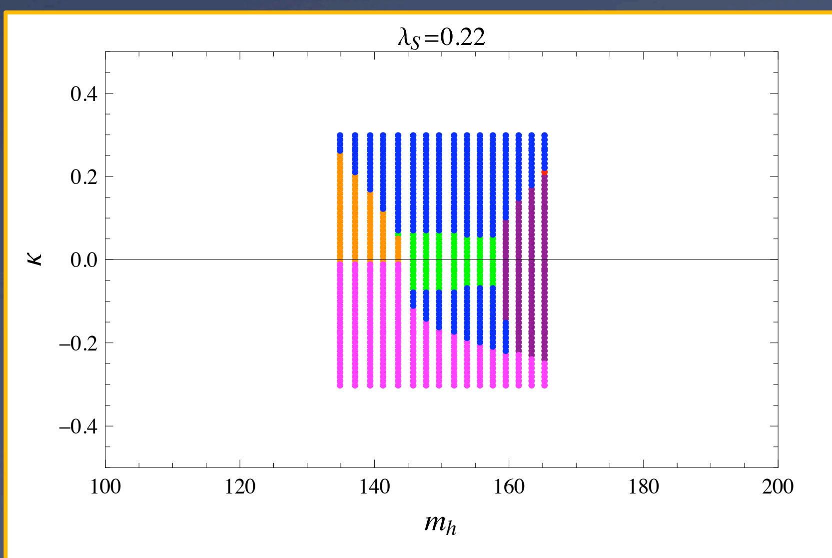
Triviality bounds:

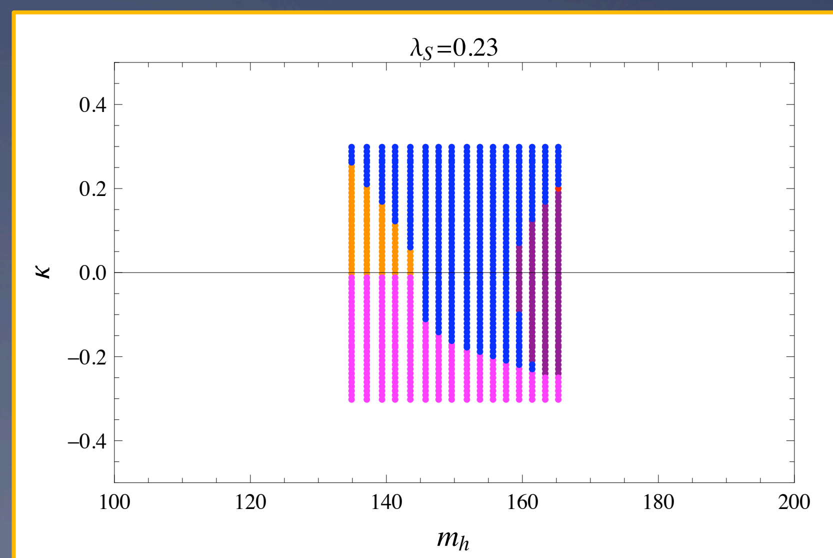
$$\bar\lambda,\ \bar\lambda_S,\ \bar\kappa\ <\ 4\pi$$

Parameter space constraints









Non minimal coupling

Focusing on the scalar and gravitational sector of this model the tree level action in the Jordan frame is specified by:

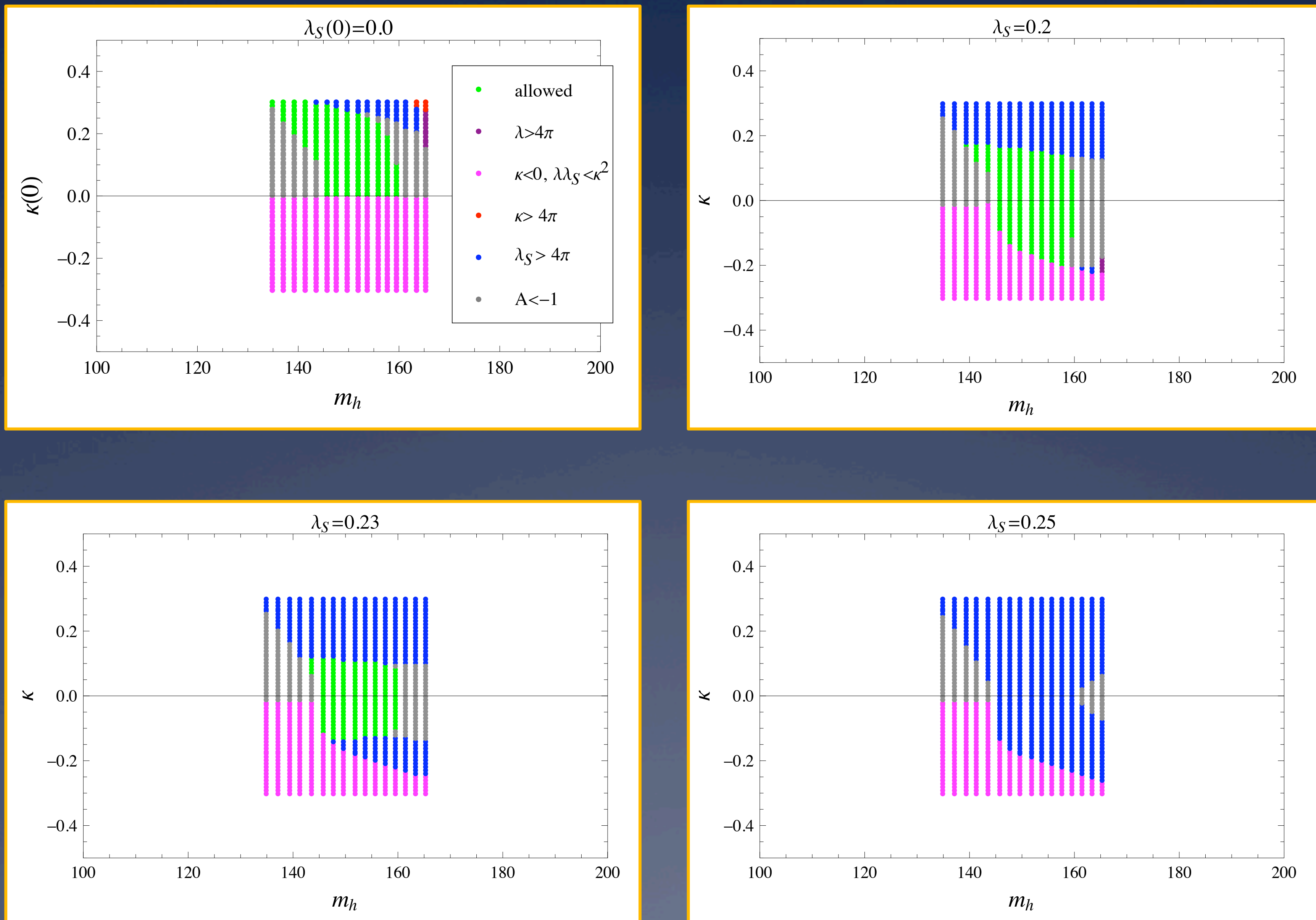
$$\Gamma = \int d^4x\sqrt{-g}\Big[\Lambda + \frac{1}{2}m_{Pl}^2 R + (D_\mu H)^\dagger g^{\mu\nu} D_\nu H - V(H^\dagger H) + \xi R(H^\dagger H - \frac{v^2}{2})$$
$$+\frac{1}{2}\partial_\mu S g^{\mu\nu}\partial_\nu S - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_S}{4}S^4 + \frac{1}{2}\xi_S R S^2 - \kappa S^2(H^\dagger H - \frac{v^2}{2}) + \cdots\Big]$$

- The one-loop renormalization group improved effective action can be calculated by using a modified propagator for the physical Higgs field.

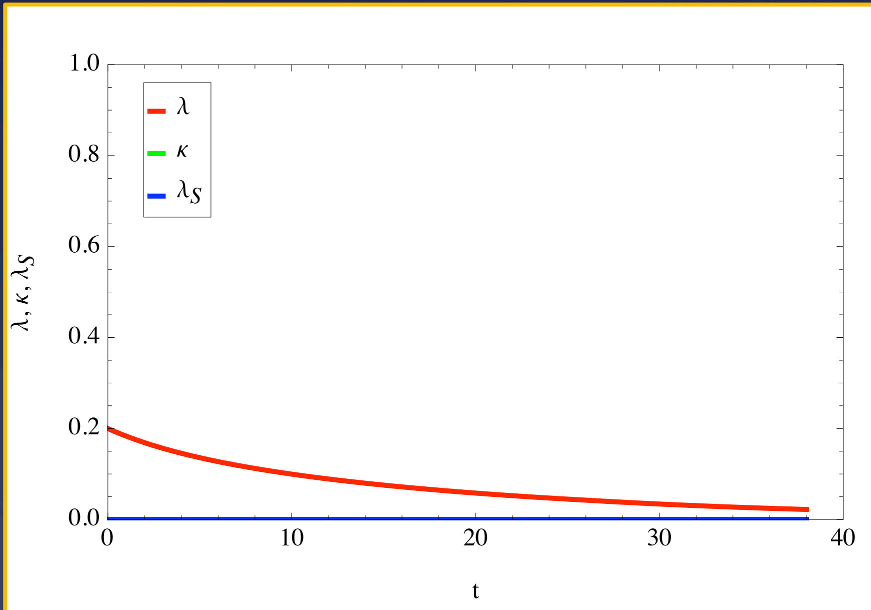
- In particular, the renormalization group functions includes a suppression factor for each physical Higgs line contributing to the function.

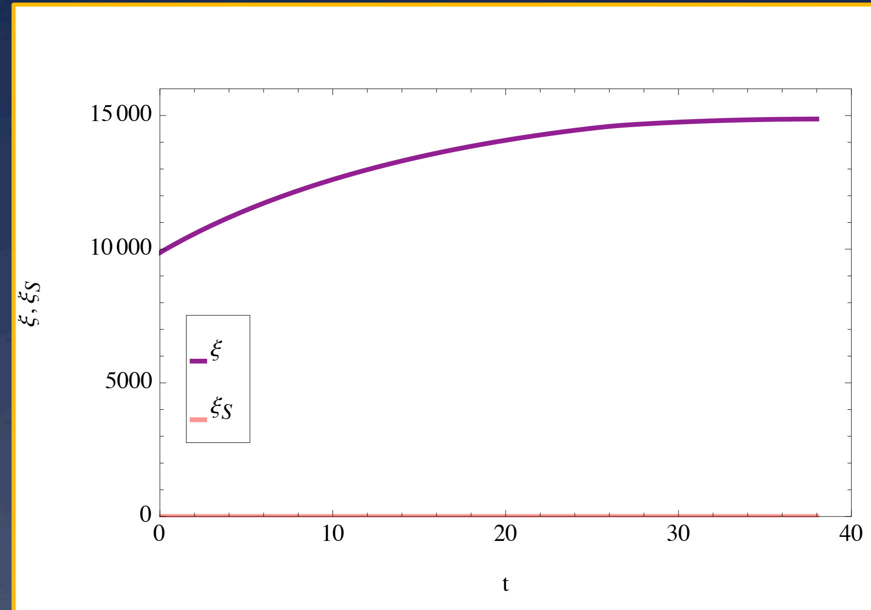
- Cosmological quantities can most easily be calculated in the Einstein frame which is obtained by rescaling the metric.

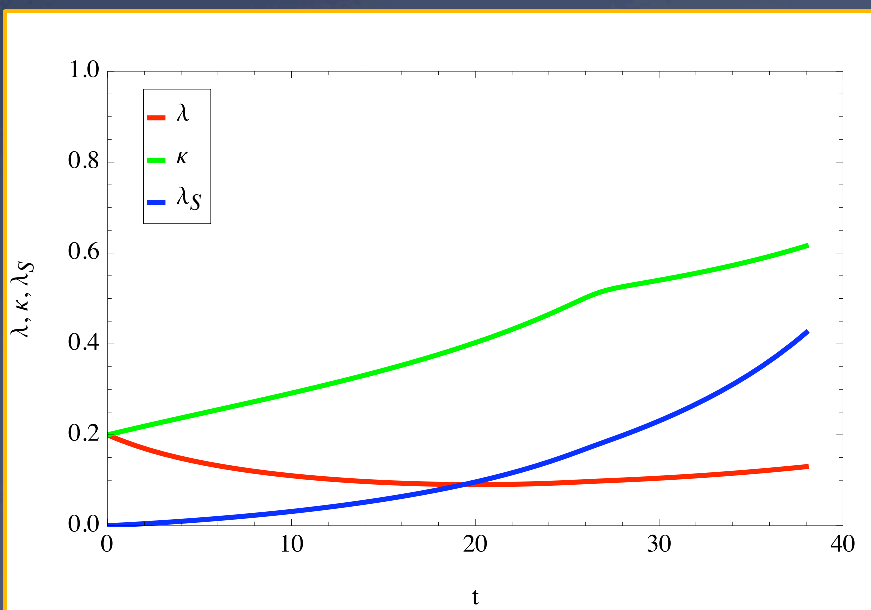
Parameter space constraints

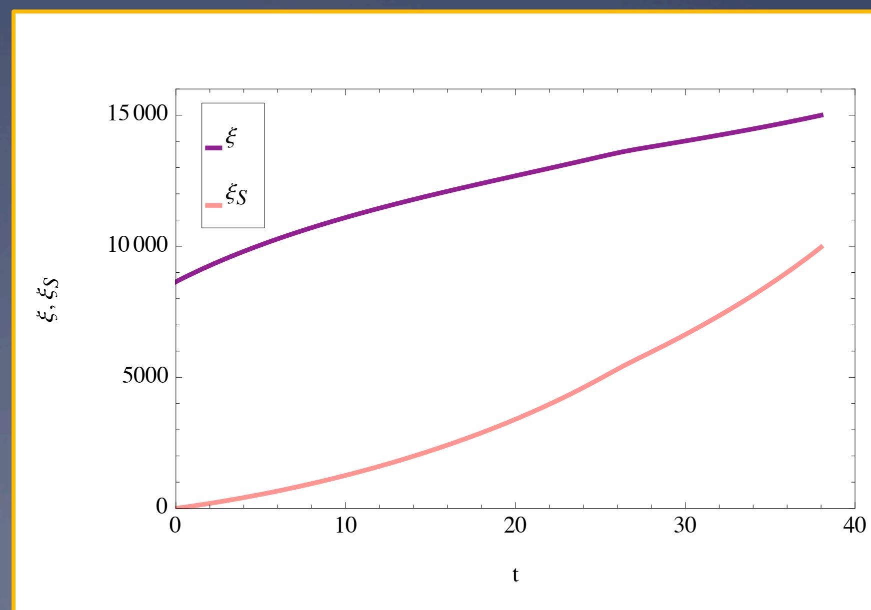


Characteristic running of the coupling constants









Procedure

o The renormalization group improved effective potential for the physical Higgs field is determined.

o The modified renormalization group equations are solved numerically with the initial conditions for t=0 being given at $\mu = m_t$.

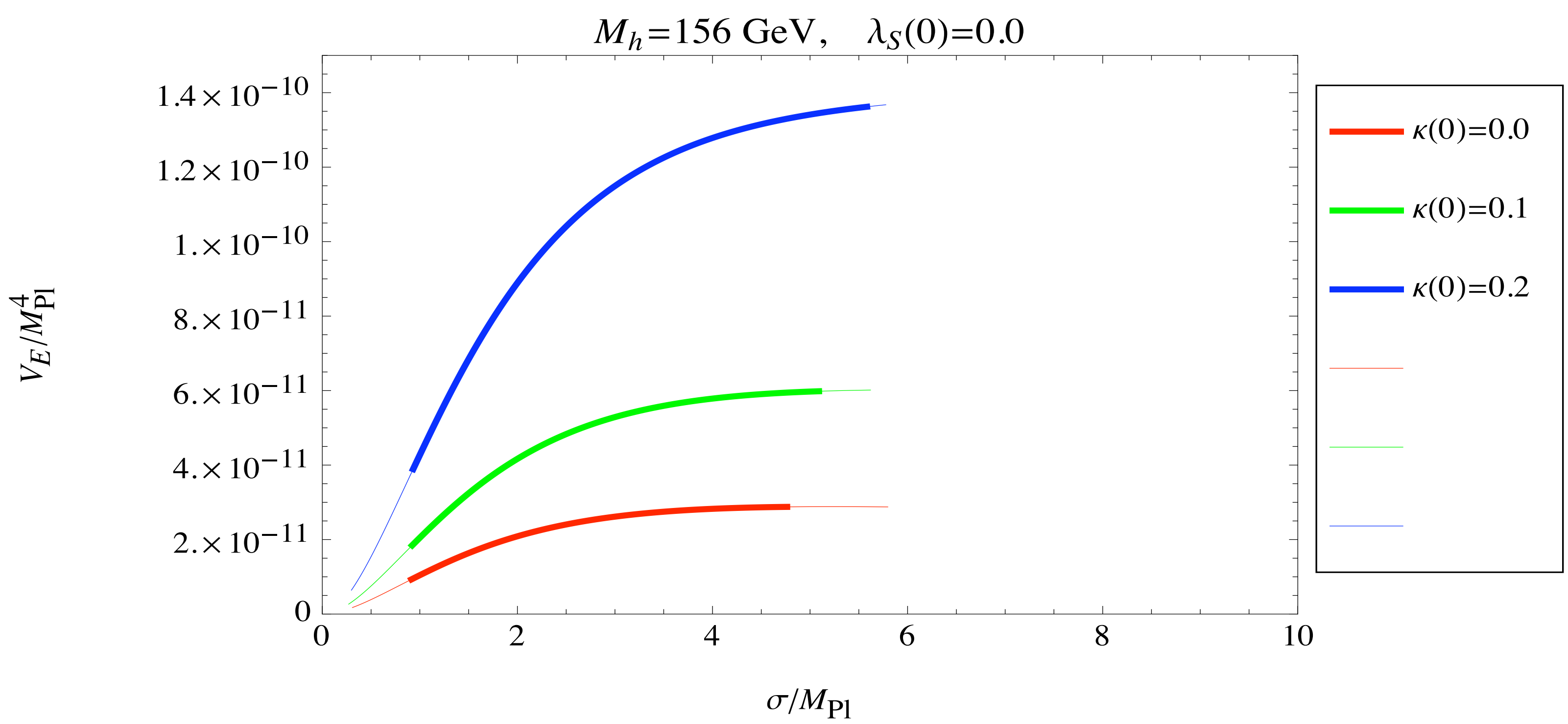
o The value of $\xi(0)$ is determined so that at the initial point of the slow roll inflation the non-minimal coupling constant $\xi(t_i)$ is such that the calculated value of the amplitude of density perturbations agrees with the measured value.

o The Higgs-inflaton exits inflation when the slow roll parameter $\varepsilon(t_f) = 1$.

o The initial point of inflation is defined so that the number of e-folds of expansion between t_i and t_f is equal to 60.

o The spectral index, its running and the tensor to scalar ratio are predicted quantities which depend on the Higgs mass as well as the Higgs to dark matter coupling.

The Higgs-inflaton effective potential



- The presence of the singlet scalar dark matter is seen to change the shape of the Higgs-inflaton effective potential.
- Thick lines indicate the region where inflation takes place.

Relation between slow roll and cosmological parameters

The renormalization group invariant slow roll inflationary parameters are given by:

$$\epsilon = \frac{1}{2} m_{Pl}^2 \left[\frac{1}{\bar{V}_E} \frac{d\bar{V}_E}{d\sigma} \right]^2$$

$$\eta = m_{Pl}^2 \frac{1}{\bar{V}_E} \frac{d^2\bar{V}_E}{d\sigma^2}$$

$$\zeta^2 = m_{Pl}^4 \frac{1}{\bar{V}_E} \frac{d^3\bar{V}_E}{d\sigma^3} \frac{1}{\bar{V}_E} \frac{d\bar{V}_E}{d\sigma}$$

Slow roll inflation predicts the spectral index, its running, and the tensor to scalar ratio to be:

$$n_s = 1 - 6\epsilon + 2\eta$$

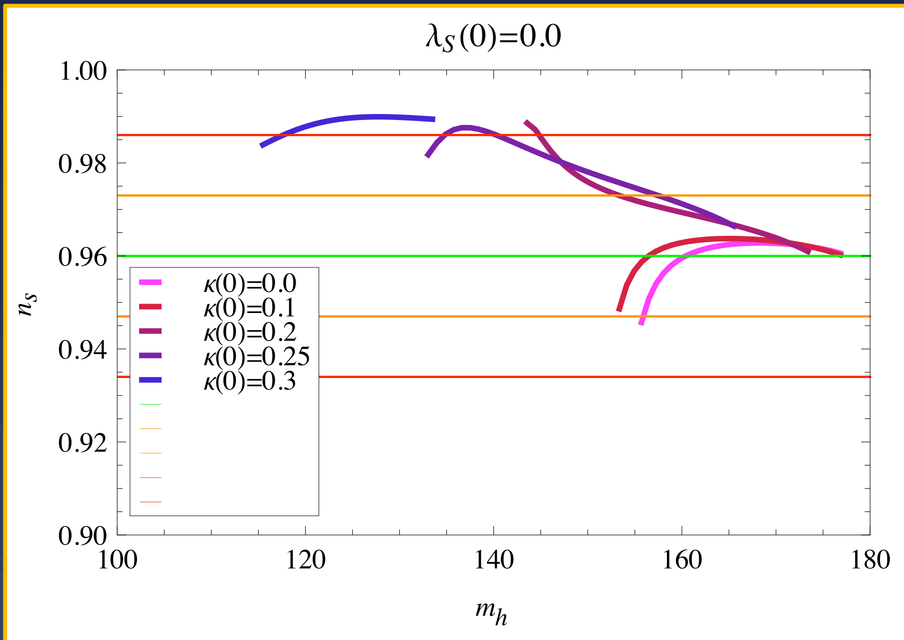
$$\alpha = -24\epsilon^2 + 16\epsilon\eta - 2\zeta^2$$

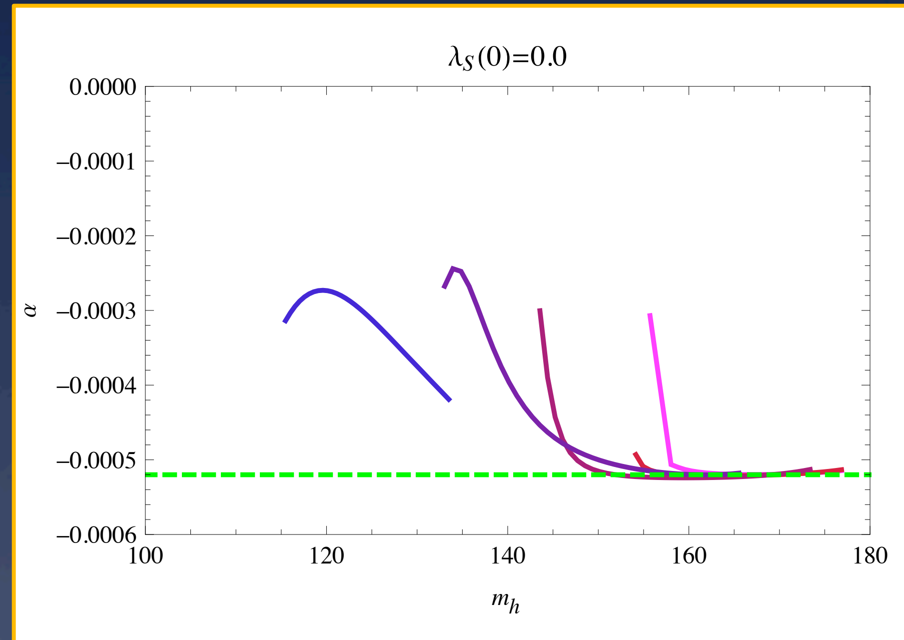
$$r = 16\epsilon$$

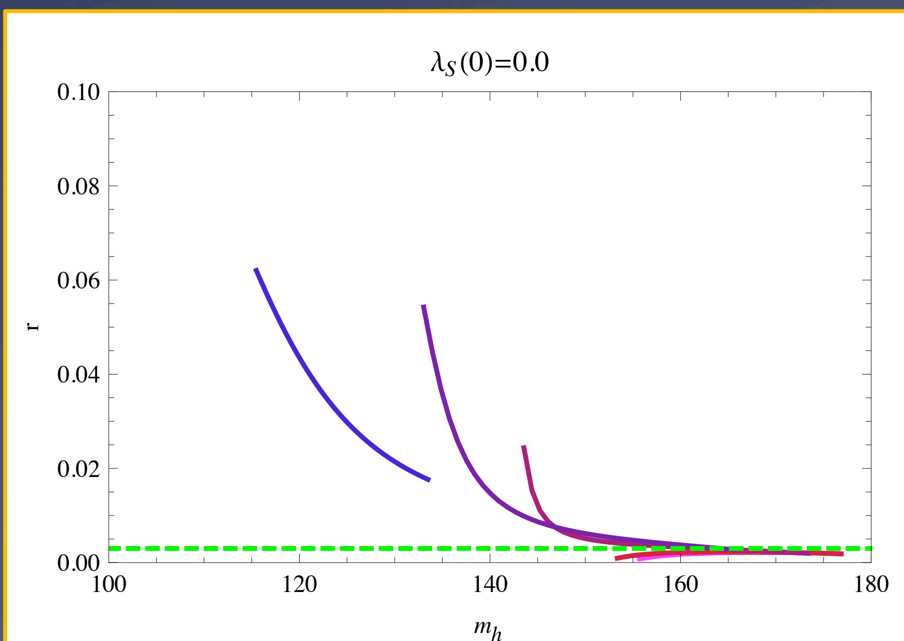
Observational constraints:

$$0.93 < n_s < 0.994$$

$$r < 0.22$$

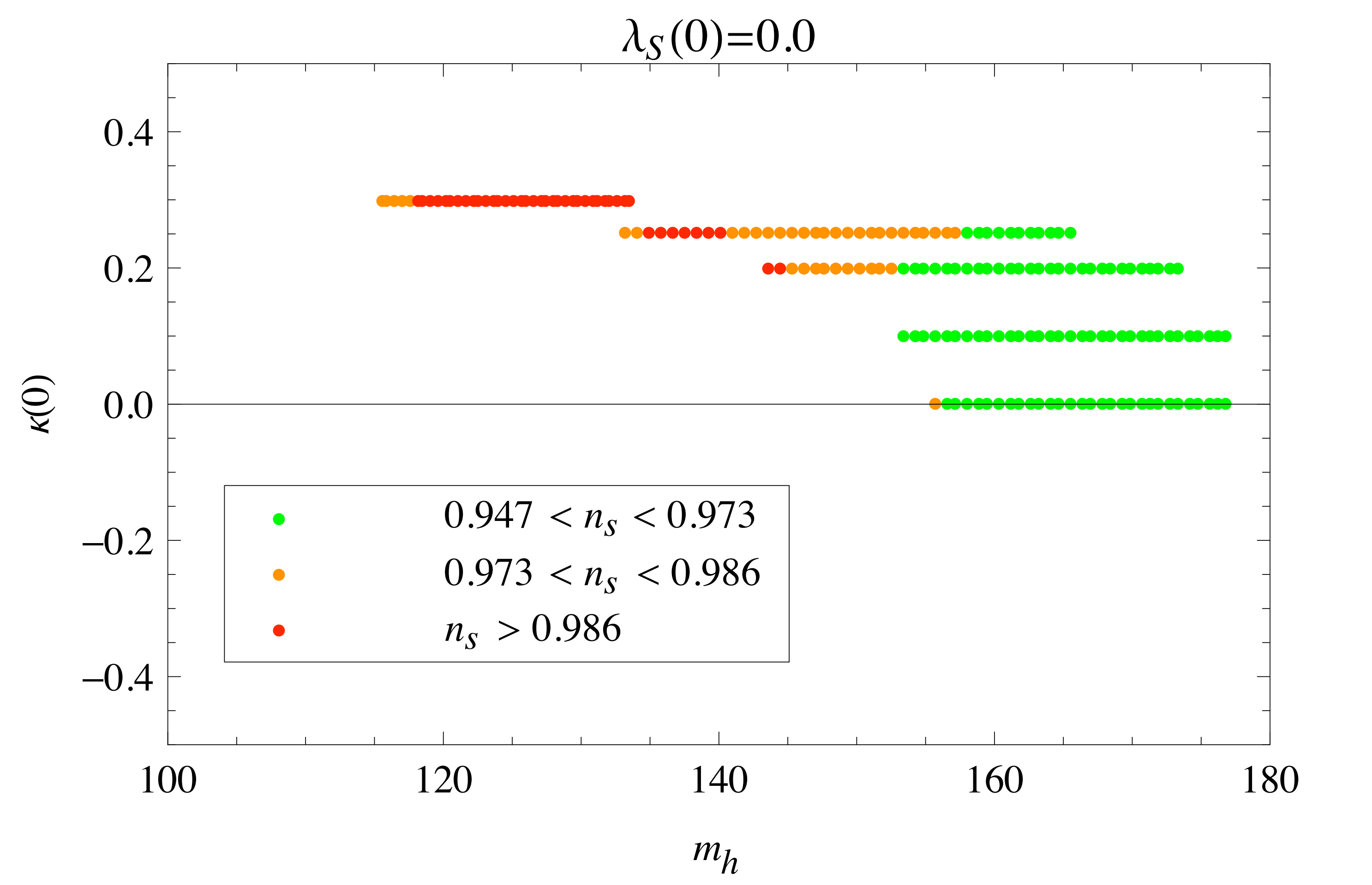






- Inflation parameters as a function of the Higgs mass for varying values of κ(0).
- Higgs masses in the lower range are obtained for larger values of κ(0).
- The spectral index takes higher values at larger values of κ(0).
- One and two sigma observational limits are indicated for the spectral index.
- Dashed green lines indicate classical values.

Parameter space constraints due to spectral index



- Some tension with observation for smaller Higgs masses

Summary

- We considered a minimally extended Standard Model.

- The Higgs field is the inflaton field. A non-minimal coupling to the scalar curvature is included with sizable coupling constant.

- A singlet scalar provides the dark matter.

- The radiative corrections due to the coupling of the Higgs and the singlet provide a cosmological bound on the Higgs mass that is shifted to lower mass values as compared to the Higgs inflaton Standard Model alone.

- Lower Higgs masses are obtained for stronger interaction between the Higgs field and the scalar. This is favored by the dark matter relic abundance constraint.

- Some tension arises with the observed range of the spectral index for lower values of the Higgs mass.