A possible link between inflation and dark matter

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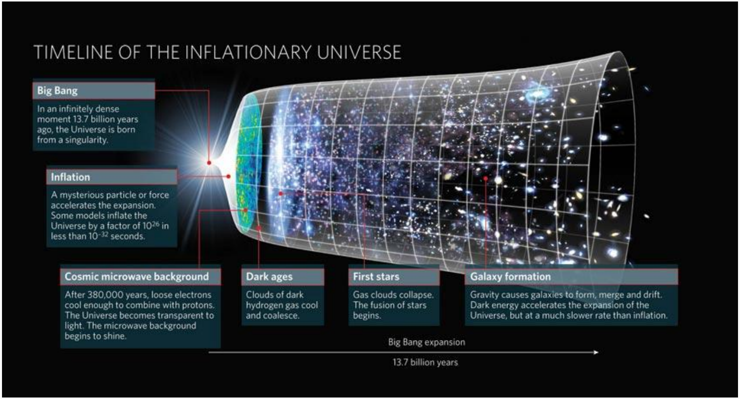
based on

*[JK, W. Park, and P. Ko, JCAP**1702**, 003 (2017)]
*[JK and J. McDonald, PRD**95**, 123537 (2017)]
*[JK and J. McDonald, PRD**95**, 103501 (2017)]

Cosmic inflation

Cosmic inflation has emerged as a solution of the standard Big Bang cosmological problems, such as horizon problem, flatness problem, and so on. [Guth, Phys. Rev. D **23**, 347-356 (1981)] [Linde, Phys. Lett. B **175**, 395-400 (1986)]



[Image from NASA/WMAP Science Team]

Cosmic inflation

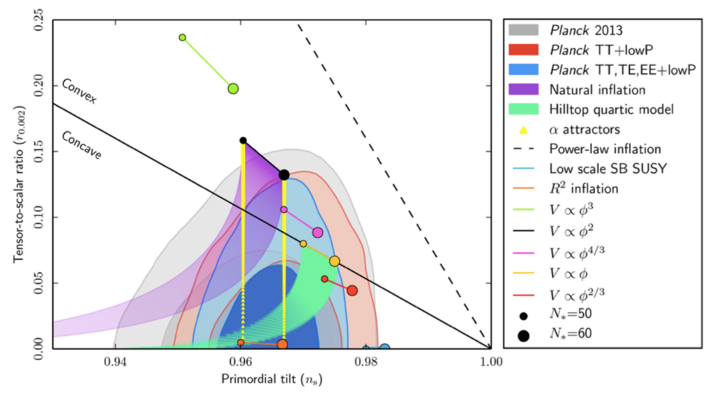
Cosmic inflation, in the simplest form, may be realised in particle physics with single scalar field ϕ.

Cosmic inflation can explain not only the homogeneity and isotropy of our Universe, but it also generates small anisotropies due to the quantum fluctuations $\phi(t, \mathbf{x}) = \overline{\phi}(t) + \delta\phi(t, \mathbf{x}) \rightarrow$ Structure Formation.

Cosmological observables (comparison with CMB data):

- Scalar power spectrum : $\mathcal{P}_s \sim \langle \delta\phi(\mathbf{k}_1)\delta\phi(\mathbf{k}_2) \rangle$
- Scalar spectral index : $n_s \equiv 1 + \frac{d \ln \mathcal{P}_s}{d \ln k}$
- Tensor-to-scalar ratio : $r \equiv \frac{\mathcal{P}_t}{\mathcal{P}_s}$

We now have (i) lots of experimental results and (ii) lots of theoretical models.



[Image from Planck Collaboration]

We now have (i) lots of experimental results and (ii) lots of theoretical models.

Encyclopædia Inflationaris

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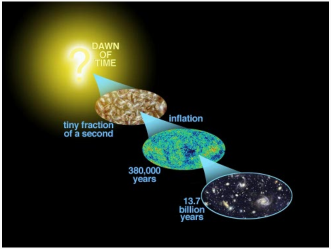
[Martin et. al., Phys. Dark Univ. **5-6**, 75 (2014)]

Mysteries

There are still several question marks:

- Before cosmic inflation?
- Initial conditions? [JK and J. McDonald, PRD**95**, 103501 (2017)]
- After inflation? [JK and J. McDonald, PRD**95**, 123537 (2017)]
- What is the inflaton?
- A link to dark matter? [JK, W. Park, and P. Ko, JCAP**1702**, 003 (2017)]



[Image from Google]

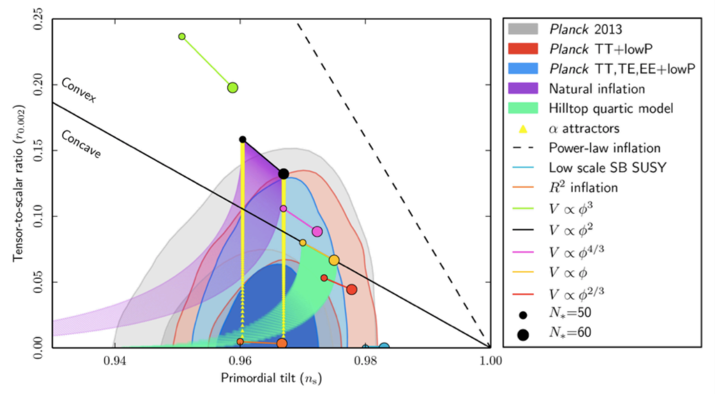
Outline

- Introduction
- The best-fit model: Plateau-type inflation
- Initial conditions problem
- Nonminimal Higgs inflation
- Realisation of Higgs inflation with Higgs portal interactions
- Summary

Plateau-type inflation

Plateau-type inflation

Let us have a look at the latest Planck result again.



Plateau-type inflation

Favoured models include

- Starobinsky's model : $R + \alpha R^2$
  [Starobinsky, Phys. Lett. **91B**, 99 (1980)]
- Nonminimally coupled model : $(1 + \xi\phi^2)R/2 - (\partial\phi)^2/2 - \lambda\phi^4$
  [Salopek et. al., Phys. Rev. D **40**, 1753 (1989)]
- α-attractor model : $V = \lambda \tanh^2(\phi/\sqrt{2\alpha})$
  [Kallosh and Linde, JCAP **1307**, 002 (2013)] [Kallosh et. al., JHEP **1311**, 198 (2013)]

Plateau-type inflation

The R^2 inflation (a.k.a. the Starobinsky model) is described by

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\rm P}^2}{2} R + \frac{1}{12M^2} R^2 \right] .$$

In the canonical Einstein frame,

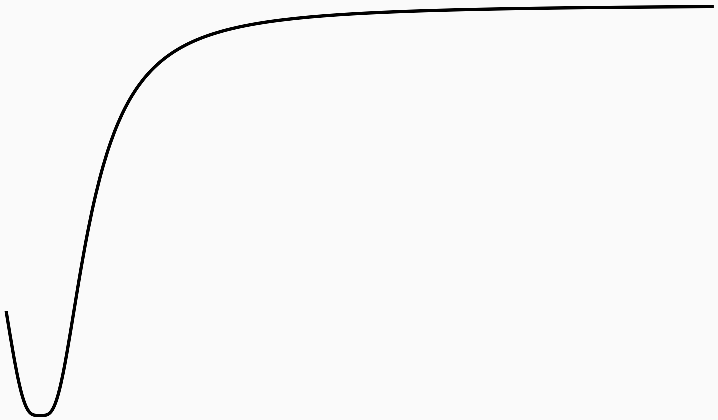
$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\rm P}^2}{2} R - \frac{1}{2} (\partial\phi)^2 - V(\phi) \right] ,$$

where the Einstein-frame potential V is given by

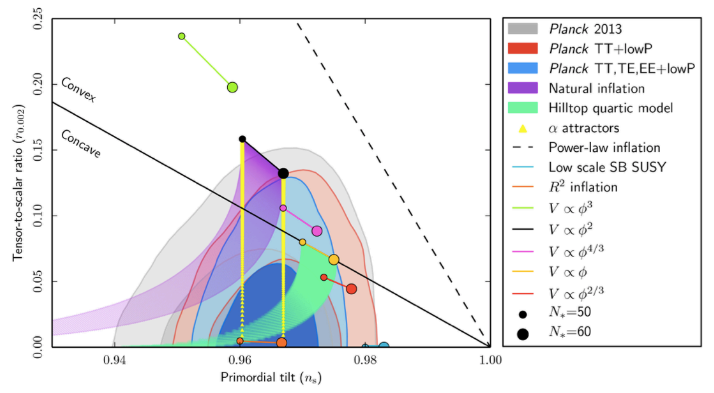
$$V(\phi) = \frac{3}{4} M_{\rm P}^4 M^2 \left(1 - e^{-\sqrt{2/3}\phi/M_{\rm P}} \right)^2 .$$

Plateau-type inflation

Potential shape:



[Interlude] Plateau inflation models



R^2 inflation vs. Nonminimally coupled inflation?

[Interlude] Plateau inflation models

It is easy to see why plateau-type models all give similar predictions on n_s and r.

Let us first consider the nonminimally coupled model.

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

One can go to the Einstein frame via Weyl rescaling:
$g_{\mu\nu} \to g_{\mu\nu}^{\rm E} = (1 + \xi\phi^2/M_{\rm P}^2) g_{\mu\nu}$.

The resultant Einstein frame action is given by

$$S = \int d^4x \sqrt{-g^{\rm E}} \left[\frac{M_{\rm P}^2}{2} R^{\rm E} - \frac{1}{2} g^{{\rm E}\mu\nu} \partial_\mu \varphi \partial_\nu \varphi - \frac{\lambda \phi^4}{4(1 + \xi\phi^2/M_{\rm P}^2)^2} \right]$$

where φ is the canonically normalised field

$$\left(\frac{d\varphi}{d\phi} \right)^2 = \frac{1 + (1 + 6\xi)\xi\phi^2/M_{\rm P}^2}{(1 + \xi\phi^2/M_{\rm P}^2)^2}$$

[Interlude] Plateau inflation models

In the large field limit, the potential becomes $V \sim \lambda/(4\xi^2)$: very flat !

Consequently the slow-roll parameter ϵ becomes very small, resulting in small tensor-to-scalar ratio, $r \simeq 16\epsilon$.

During inflation the kinetic energy density is negligible. Thus the action reduces to

$$S \simeq \int d^4x \sqrt{-g}\, \left[\frac{M_{\rm P}^2}{2} \left(1 + \xi \frac{\phi^2}{M_{\rm P}^2} \right) R - \frac{1}{4}\lambda\phi^4 \right]$$

Now the field ϕ is an auxiliary field. Integrating out the field ϕ by using its equation of motion, $\phi^2 = \xi R/\lambda$, gives

$$S \simeq \int d^4x \sqrt{-g}\, \left[\frac{M_{\rm P}^2}{2} R + \frac{\xi^2}{4\lambda} R^2 \right]$$

which is nothing but the Starobinsky model.

Plateau-type inflation

The α-attractor model, in the Einstein frame, is described by

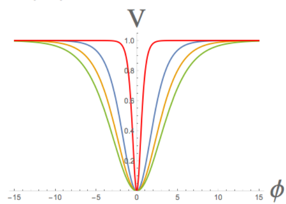
$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\rm P}^2}{2} R - \frac{1}{2}(\partial\phi)^2 - V_{\rm T,E}(\phi) \right] ,$$

where

$$V_{\rm T}(\phi) = V_0 \tanh^{2n}\left(\frac{\phi}{\sqrt{6\alpha} M_{\rm P}} \right) ,$$

$$V_{\rm E}(\phi) = V_0 \left(1 - e^{-\sqrt{2/(3\alpha)}\phi/M_{\rm P}} \right)^{2n} .$$

The E-model is similar to the Starobinsky model. The T-model potential looks like:



Plateau-type inflation

Focusing on inflationary regime, i.e., $\phi > 0$ region, all the three models (or potentials) have something in common:

existence of a plateau (or flat) region

Consequences include:

- V approaches to a constant value
- ϵ parameter is naturally small
  - $\rightarrow$ Recall: $\epsilon \sim V'/V$
- consequently r becomes small
  - $\rightarrow$ Recall: $r \sim \epsilon$
  - $\rightarrow$ Hence, consistent with Planck data

Initial conditions problem

Initial conditions of the plateau-type inflation

Note again that the plateau-type model, whether it is R^2 inflation, α-attractor models, or the nonminimal Higgs inflation, is in good agreement with the latest Planck results.

One of the features of such models is that the scalar potential approaches to a constant value in the large field limit:

$$\lim_{\phi \to \infty} V(\phi) = V_0 \ll M_{\mathrm{P}}^4 \,,$$

which is much less than the Planck energy density.

Initial conditions of the plateau-type inflation

However, in order for inflation to start in the first place, it is required to have a potential-dominated initial state over a horizon volume.

Initial conditions for inflation:

the Universe started in a chaotic initial state
with Planck-scale energy density

$$\frac{1}{2}\dot{\phi}^2 \sim \frac{1}{2}(\nabla\phi)^2 \sim V(\phi) \sim M_{\mathrm{P}}^4$$

[Linde, Phys. Lett. **129B**, 177 (1983)] [Linde, Rept. Prog. Phys. **47**, 925 (1984)]

Initial conditions of the plateau-type inflation

Several solutions

1. to modify the potential such that it increases as the inflaton field increases and reaches the Planck energy density
   [JK and J. McDonald, Phys. Rev. D **95**, 103501 (2017)]
2. for a smooth patch to be produced during the chaotic era which has the form of an open Universe, with a negative curvature term which dominates the Friedmann equation
   [Guth et al., Phys. Lett. B **733**, 112 (2014)]
3. to have a contracting era which precedes the expanding era (does not rely on a chaotic initial state)
   [J. McDonald, Phys. Rev. D **94**, 043514 (2016)]

Initial conditions of the plateau-type inflation

Two ways

1. to add non-renormalisable higher-order terms
   $\rightarrow$ changing the particle physics sector

2. to consider a conformal factor with a zero
   $\rightarrow$ particle physics sector unchanged
   $\rightarrow$ regarded as a minimal modification

Note that they are equivalent (at least at the tree level) due to the relation $V_{\mathrm{E}} = V_{\mathrm{J}}/\Omega^4$.

Initial conditions of the plateau-type inflation

Consider a general class of models

$$\xi \frac{\phi^2}{M_{\mathrm{P}}^2} \longrightarrow \xi \frac{\phi^2}{M_{\mathrm{P}}^2} \times f\left(\frac{\phi^2}{M_{\mathrm{P}}^2}\right)$$

Leading order contributions

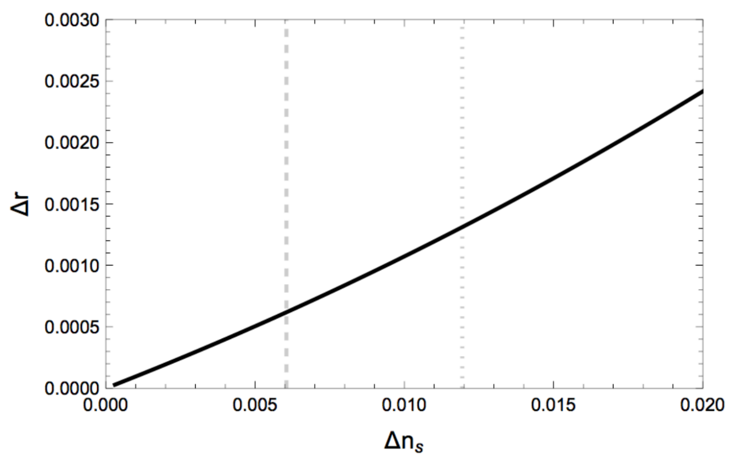
$$\Omega^2 = 1 + \xi \frac{\phi^2}{M_{\mathrm{P}}^2} \times f\left(\frac{\phi^2}{M_{\mathrm{P}}^2}\right) = 1 + \xi \frac{\phi^2}{M_{\mathrm{P}}^2} - \zeta \frac{\phi^4}{M_{\mathrm{P}}^4} + \cdots$$

with

$$\zeta = \mathcal{O}(1) \times \xi$$

Initial conditions of the plateau-type inflation

Cosmological Observables:



Nonminimal Higgs inflation

Nonminimal Higgs inflation

- NOTE:: we are talking about the Standard Model Higgs inflation. for supersymmetric extensions of the Higgs inflation, see e.g., [S. Kawai and JK, PRD**91**, 045021 (2015) and PRD**93**, 065023 (2016)]

- NOTE:: for the moment, we are assuming that the SM is valid all the way up to the inflation scale.

Nonminimal Higgs inflation

[D. S. Salopek *et. al.*, Phys. Rev. D **40**, 1753 (1989)], [F. L. Bezrukov and M. Shaposhnikov, Phys. Lett. B **659**, 703 (2008)]

- The nonminimal Higgs inflation is described by the action

$$\int d^4x \sqrt{-g_{\mathrm{J}}} \left[\frac{M_{\mathrm{P}}^2}{2} R_{\mathrm{J}} + \frac{1}{2}\xi_h h^2 R_{\mathrm{J}} - \frac{1}{2} g_{\mathrm{J}}^{\mu\nu} \partial_\mu h \partial_\nu h - V_{\mathrm{J}}(h) \right] ,$$

  where the subscript J stands for the Jordan frame.
- It is convenient to go to the Einstein frame, where it is easy to see the role of the nonminimal coupling term and easy to compute cosmological observables.
- The transformation from the Jordan frame to the Einstein frame is called the Weyl rescaling (a.k.a. conformal transformation).

Nonminimal Higgs inflation

- The most generic Jordan-frame action,

$$\int d^4x\,\sqrt{-g_{\rm J}}\,\left[\frac{M_{\rm P}^2}{2}\Omega^2(\phi)R_{\rm J}-\frac{1}{2}g_{\rm J}^{\mu\nu}Z(\phi)\partial_\mu\phi\partial_\nu\phi-V_{\rm J}(\phi)\right]\,,$$

can be transformed to the Einstein frame, via Weyl rescaling $g_{\rm J}^{\mu\nu}\to g_{\rm E}^{\mu\nu}=\Omega^{-2}g_{\rm J}^{\mu\nu}$, as

$$\int d^4x\,\sqrt{-g_{\rm E}}\,\left[\frac{M_{\rm P}^2}{2}R_{\rm E}-\frac{1}{2}g_{\rm E}^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi-V_{\rm E}(\varphi)\right]\,.$$

- φ : canonically normalised field
- $V_{\rm E}$: Einstein-frame potential

$$\left(\frac{d\varphi}{d\phi}\right)^2=\frac{Z}{\Omega^2}+\frac{3M_{\rm P}^2}{2\Omega^4}\left(\frac{d\Omega^2}{d\phi}\right)^2\,,\qquad V_{\rm E}=\frac{V_{\rm J}}{\Omega^4}\,.$$

Nonminimal Higgs inflation

- In the case of the nonminimal Higgs inflation,

$$\Omega^2 = 1 + \xi_h h^2/M_{\rm P}^2\,, \quad Z = 1\,, \quad V_{\rm J} = \lambda_h h^4/4\,.$$

- Hence, the potential in the Einstein frame takes

$$V_{\rm E} = \frac{\lambda_h h^4}{4(1+\xi_h h^2/M_{\rm P}^2)^2}\,.$$

- In the large field limit, the potential becomes very flat!

$$V_{\rm E} \to \left(\frac{\lambda_h}{4\xi_h^2}\right) M_{\rm P}^4\,.$$

  - Planck normalisation (or scalar power spectrum at CMB scale): $\lambda_h/\xi_h^2 \sim 10^{-10}$.

Nonminimal Higgs inflation

- The effect of the nonminimal coupling is to flatten the potential.
- Without taking quantum corrections into account, the plateau potential suppresses the tensor-to-scalar ratio.
- One may see this from

$$n_s \approx 1 - 6\epsilon + 2\eta\,, \quad r \approx 16\epsilon\,,$$

  where

$$\epsilon \equiv \frac{M_{\rm P}^2}{2}\left(\frac{dV_{\rm E}/d\varphi}{V_{\rm E}}\right)^2\,, \quad \eta \equiv M_{\rm P}^2\frac{d^2V_{\rm E}/d\varphi^2}{V_{\rm E}}\,.$$

- With $\lambda_h \simeq 0.1$, one obtains $n_s \approx 0.966$ and $r \approx 0.003$, which are in excellent agreement with the latest Planck results.

Nonminimal Higgs inflation

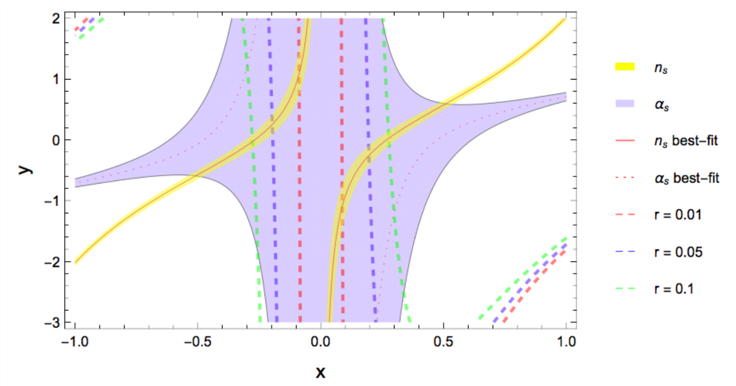
- Taking quantum corrections into account, i.e., $\lambda_h = \lambda_h(t)$, one may compute cosmological observables, such as spectral index n_s and tensor-to-scalar ratio r.
- NOTE:: We are ignoring the running of ξ_h for the moment.
- For example, the tensor-to-scalar ratio is given by

$$r \approx \frac{64}{3\xi_h^2}\left(\frac{M_{\rm P}}{h}\right)^4\left[1 + x\frac{\xi_h h^2}{4M_{\rm P}^2}\right]^2 ,$$

where $x \equiv (d\lambda_h/dt)/\lambda_h$ characterises the running of the quartic coupling.

Nonminimal Higgs inflation

- Cosmological observables:



Here $x \equiv (d\lambda_h/dt)/\lambda_h$ and $y \equiv (d^2\lambda_h/dt^2)/(d\lambda_h/dt)$.

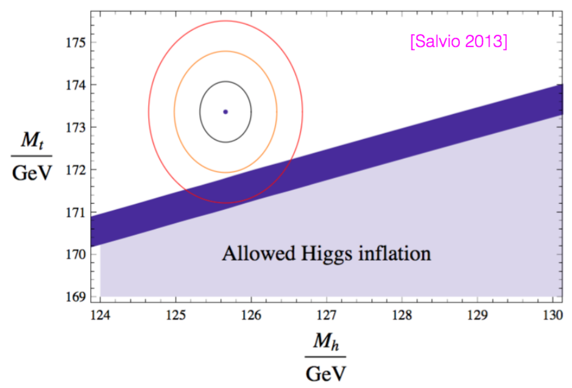
Nonminimal Higgs inflation

- So, in summary, the nonminimal Higgs inflation is consistent with Planck results at classical level (small r, large ξ_h).
- At quantum level, the model predicts a largish r with small ξ_h, but within the Planck bound.

- End of the story?

Nonminimal Higgs inflation

- Not quite so!



- Furthermore, the Standard Model itself is not capable of explaining the dark matter.
- Really?

Nonminimal Higgs inflation

- It has recently been pointed out that primordial black holes may be formed during (or near the end of) inflation and may play the role of dark matter.

  see e.g., [J. M. Ezquiaga, J. Garcia-Bellido, and E. R. Morales, arXiv:1705.04861]
- That is mainly due to the appearance of a near-inflection point near the end of inflation for a finely tuned top quark mass.
- Nevertheless, the assumption that the SM is true all the way up to the inflationary scale seems too much. e.g., neutrino masses, baryon asymmetry, ...

Higgs-portal assisted Higgs inflation

Extending the Standard Model

- The Standard Model needs to be extended in order to explain, at least, the existence of dark matter.
- Higgs-portal interaction is generic in hidden-sector dark matter models.
- In this work, we choose to work with the SFDM (singlet fermion dark matter) model, where the hidden sector consists of a singlet scalar field and a fermionic DM-candidate field.
- The SM sector and the hidden sector communicate through the Higgs-portal interaction:

$$V_{\mathrm{portal}} = \mu_{SH} S |H|^2 + \frac{1}{2} \lambda_{SH} S^2 |H|^2 \,.$$

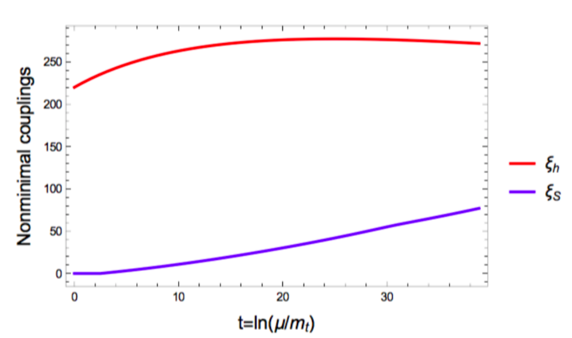
The extra scalar field S, instead of the Standard Model Higgs field H, may play the role of inflaton; see e.g., [R. N. Lerner and J. McDonald, Phys. Rev. D **80**, 123507 (2009); **83**, 123522 (2011)].

Higgs-portal assisted Higgs inflation

- It is important to note that the nonminimal coupling of the S field,

$$\frac{1}{2}\xi_S S^2 R\,,$$

is generated via RG runnings.



Higgs-portal assisted Higgs inflation

Relevant parameter list:

- λ_S : quartic coupling of S field
- λ_ψ : coupling between S and ψ, $\lambda_\psi S\overline{\psi}\psi$
- λ_{SH} : portal coupling
- α : mixing angle between the dark Higgs and the SM Higgs
- m_S : mass of S field
- ξ_S : nonminimal coupling of S to gravity

Note that ξ_h is NOT a free parameter; shall be determined by the Planck normalisation, $\mathcal{P}_S \approx 2.2 \times 10^{-9}$.

Higgs-portal assisted Higgs inflation

Relevant parameter list:

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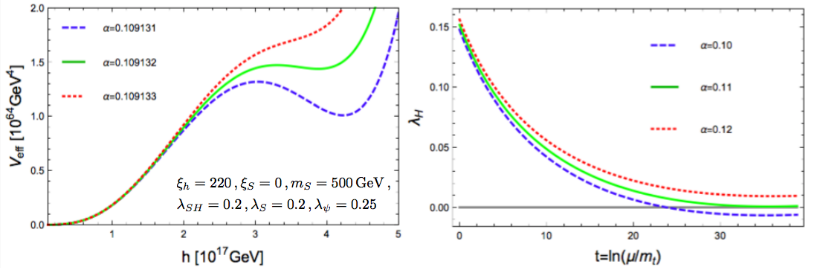
- λ_{SH} : portal coupling
- α : mixing angle between the dark Higgs and the SM Higgs
- m_S : mass of S field
- ξ_S : nonminimal coupling of S to gravity

We are interested in the SM Higgs inflation: $\xi_S = 0$ initially.

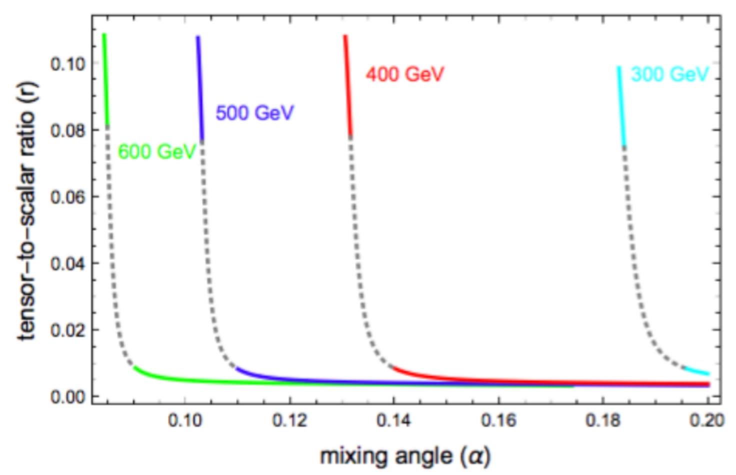
Higgs-portal assisted Higgs inflation

The role of α and m_S is to control the behaviour of λ_h, and hence the potential shape.



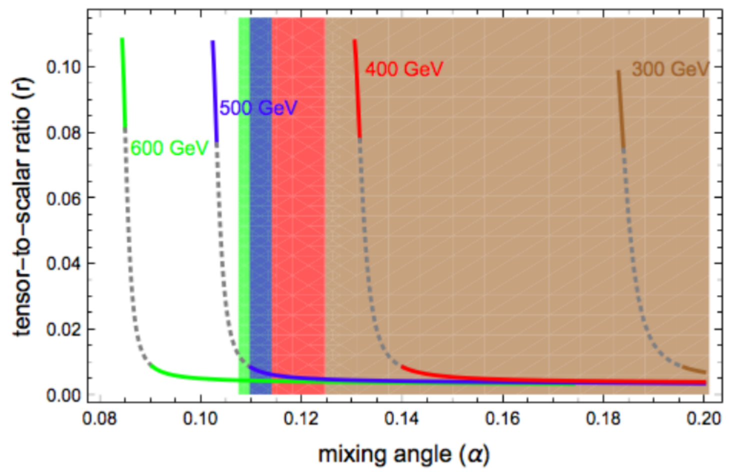
Higgs-portal assisted Higgs inflation

We performed a numerical analysis to find cosmological observables, by considering (i) perturbativity, (ii) vacuum stability, and (iii) Planck 2015 data.



Higgs-portal assisted Higgs inflation

We can further constrain parameter space by considering (i) dark matter relic density and (ii) dark matter direct detection from LUX bound.



Conclusion

Summary

In this talk, we discussed

- plateau-type inflation models,
- initial conditions problem of the plateau-type models,
- nonminimal Higgs inflation in the Standard Model,
- and realisation of Higgs inflation in the presence of Higgs-portal interaction.

Thank you