WIMP inflation from a scalar singlet.

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Two big problems of cosmology

- We observe the gravitational interactions of dark matter (DM) over many different astrophysical and cosmological scales, but we do not have any experimental information about its particle nature.
- We have strong evidence that the Universe underwent a period of primordial inflation consistent with the generic predictions for a scalar inflaton, but we do not know the identity of the responsible field(s).
- The non-observation of any new weak-scale states at the LHC may indicate that any extension of the Standard Model (SM) to include DM should be rather simple.
- Similarly, the non-observation of non-Gaussianity by Planck suggests that inflation is also minimal, i.e. due to a single scalar field.



A scalar singlet

- > Here we focus on a particularly simple extension of the SM, namely an additional gauge singlet scalar *s*, which is stabilised by a Z_2 -symmetry.
- The scalar singlet s is then a typical weakly interacting massive particle (WIMP), which obtains its relic abundance from the thermal freeze-out of its interactions with the SM Higgs h (so-called Higgs Portal DM).
- Furthermore, if the scalar singlet has a non-minimal coupling to gravity, it can be responsible for inflation, in close analogy to the model of Higgs Inflation with the scalar singlet taking the role of the SM Higgs.
- In other words, in these models the same scalar particle drives inflation and later freezes out to become cold DM ("WIMP inflation").



Why now?

- The idea of a singlet scalar as both inflaton and DM can be tested and constrained in a number of different ways:
 - Precise measurements of the inflation observables (e.g. by Planck)
 - DM detection experiments (such as LUX)
 - The mass of the Higgs boson and the top quark, which determine the running of the couplings between the scale of inflation and the weak scale.
 - Measurements of the properties of the SM Higgs boson (in particular branching ratios).
- In this talk, we will confront the WIMP inflation model with the latest observational and experimental data and demonstrate that – in spite of its simplicity – the model still has a large viable parameter space.



The model

> We take s to be a real gauge singlet scalar. The action for the model is

$$S_{\rm J} = \int \sqrt{-g} \,\mathrm{d}^4 x \Big[\mathcal{L}_{\overline{\rm SM}} + (\partial_\mu H)^\dagger (\partial^\mu H) + \frac{1}{2} \partial_\mu s \,\partial^\mu s \\ - \frac{m_{\rm P}^2 R}{2} - \xi_h \,H^\dagger H \,R - \frac{1}{2} \,\xi_s \,s^2 \,R - V(s^2, H^\dagger H) \Big]$$

where

$$V(s^2, H^{\dagger}H) = \lambda_h \left[\left(H^{\dagger}H \right) - \frac{v^2}{2} \right]^2 + \frac{1}{2} \lambda_{hs} s^2 H^{\dagger}H + \frac{1}{4} \lambda_s s^4 + \frac{1}{2} m_{s_0}^2 s^2$$

with v = 246 GeV and $H = (h+v, 0)/\sqrt{2}$.

We assume that the non-minimal couplings satisfy ξ_s ≫ ξ_h. As a result, the minimum of the potential at large s and h will be very close to h = 0 and inflation will occur along the s-direction.



Predictions for inflation

In order to calculate the observables predicted by inflation, we perform a conformal transformation to the Einstein frame, where the non-minimal coupling to gravity disappears

$$S_{\rm E} = \int \sqrt{-\tilde{g}} \, \mathrm{d}^4 x \left(\tilde{\mathcal{L}}_{\overline{SM}} - \frac{m_{\rm P}^2 \tilde{R}}{2} + \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \chi_s \partial_\nu \chi_s - U(\chi_s, 0) \right)$$

with $U(\chi_s, 0) = \frac{\lambda_s \, s^4(\chi_s)}{4 \, \Omega^4}$.

The Einstein-frame action can be used to perform the conventional analysis of inflation and calculate the curvature perturbation spectrum.

$$n_s^{\text{tree}} \approx 1 - \frac{2}{\tilde{N}} - \frac{3}{2\tilde{N}^2} + \mathcal{O}\left(\frac{1}{\tilde{N}^3}\right) = 0.965 ,$$
$$r^{\text{tree}} \approx \frac{12}{\tilde{N}^2} + \mathcal{O}\left(\frac{1}{\xi_s \tilde{N}^2}\right) = 3.6 \times 10^{-3} ,$$

As long as radiative corrections are small, the model predictions are therefore in good agreement with the most recent Planck results.























Connecting inflation and dark matter

In order to connect the inflationary observables to the measured SM parameters and the DM phenomenology, we need to calculate the evolution of all couplings under the RG equations.



Solid lines: s >> h (relevant for inflation); dotted lines: h >> s (relevant for vacuum stability)



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- > We fix $\xi_s(m_p)$ by imposing the correct amplitude of the scalar power spectrum and $m_s(m_t)$ by requiring that our model reproduces the observed DM relic abundance.
- > The phenomenology of the model depends only very mildly on $\xi_h(m_P)$, so that effectively there are only two free parameters: λ_s and λ_{hs} .



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Note that the scalar singlet *s* gives a positive contribution to the running of the quartic Higgs coupling. In this specific example, λ_h remains positive all the way to the Planck scale and hence the electroweak vacuum remains stable.



Results: High-mass region



For $\lambda_{hs} > 0.2$, corresponding to m_{s} > 700 GeV, radiative corrections are large enough to stabilise the electroweak vacuum all the way to the Planck scale.

- For λ_{hs} > 0.6, corresponding to 0.015 > m_{s} > 2 TeV, radiative corrections become so large that n_s is in 0.010 tension with the bound from 0.005 Planck.
 - For $\lambda_{s} > 0.3$, the scalar couplings become non-perturbative below the scale of inflation.
 - The interesting parameter region > $0.2 < \lambda_{hs} < 0.6$ can be fully explored by upcoming direct detection experiments such as XENON1T.



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Results: Low-mass region



- > In the low-mass region, λ_{hs} is very small and hence radiative corrections to the inflationary potential are completely negligible.
- > The allowed range of values for λ_{hs} spans two orders of magnitude and is hence much harder to probe in direct detection experiments.
 - > If indeed m_s is very close to $m_h/2$, and λ_s , $\lambda_{hs} < 10^{-3}$, it will be a great challenge to test the model predictions with cosmological or particle physics measurements.



Unitarity violation

- When calculating radiative corrections to the inflationary potential, we have to ensure that perturbation theory remains valid up to sufficiently large field values.
- For Higgs inflation, the naïve calculation yields that unitarity is violated above $\Lambda \sim \bar{h}/\sqrt{\xi_h}$, where \bar{h} is the background value of *h* and $\xi_h \sim 10^5$. It is therefore typically impossible to have $\Lambda \gg \bar{h}$.
- For WIMP inflation with a real scalar singlet, the formula (in the large-field regime) is modified to

$$\Lambda \sim \frac{\sqrt{\xi_s}}{\xi_h} \overline{s}$$

which allows for $\Lambda \gg \overline{s}$ provided $\xi_{\rm h}$ is sufficiently small.





Conclusions

- The origin of inflation and the nature of DM may have a common explanation in terms of a real gauge singlet scalar.
- Given the tight constraints on many DM candidates and the strong bounds on models for inflation, it is quite remarkable that one of the simplest models addressing both problems still has a large allowed parameter space.
- Furthermore, the scalar singlet can potentially stabilise the electroweak vacuum up to the Planck scale and at the same time avoid the problem of unitarity-violation present in conventional models of Higgs inflation.
- Nevertheless, the model is highly predictive and direct detection experiments will soon reach the sensitivity necessary to probe almost the entire parameter space relevant for phenomenology.



Backup



Predictions for inflation

In order to calculate the observables predicted by inflation, we perform a conformal transformation to the Einstein frame, where the non-minimal coupling to gravity disappears.

$$\tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}, \qquad \Omega^2 = 1 + \frac{\xi_s s^2}{m_{\rm P}^2}$$

> Moreover, we define a new field χ_s via

$$\frac{\mathrm{d}\chi_s}{\mathrm{d}s} = \sqrt{\frac{\Omega^2 + 6\,\xi_s^2\,s^2/m_\mathrm{P}^2}{\Omega^4}}$$

We then obtain the Einstein frame action

$$\begin{split} S_{\rm E} &= \int \sqrt{-\tilde{g}} \,\mathrm{d}^4 x \left(\tilde{\mathcal{L}}_{\overline{SM}} - \frac{m_{\rm P}^2 \,\tilde{R}}{2} + \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \chi_s \partial_\nu \chi_s - U(\chi_s, 0) \right) \\ \text{with } U(\chi_s, 0) &= \frac{\lambda_s \, s^4(\chi_s)}{4 \,\Omega^4} \,. \end{split}$$

This expression can be used to perform the conventional analysis of inflation and calculate the curvature perturbation spectrum.



Predictions for inflation

In particular, the Einstein frame slow-roll parameters are given by

$$\begin{split} \tilde{\epsilon} &= \frac{m_{\rm P}^2}{2} \left(\frac{1}{U} \frac{\mathrm{d}U}{\mathrm{d}\chi_s} \right)^2 \\ \tilde{\eta} &= \frac{m_{\rm P}^2}{U} \frac{\mathrm{d}^2 U}{\mathrm{d}\chi_s^2} , \\ \tilde{\xi}^2 &= \frac{m_{\rm P}^4}{U^2} \frac{\mathrm{d}U}{\mathrm{d}\chi_s} \frac{\mathrm{d}^3 U}{\mathrm{d}\chi_s^3} . \end{split}$$

> The classical (tree-level) predictions are

$$n_s^{\text{tree}} \approx 1 - \frac{2}{\tilde{N}} - \frac{3}{2\tilde{N}^2} + \mathcal{O}\left(\frac{1}{\tilde{N}^3}\right) = 0.965 ,$$
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