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PARTICLE PHYSICS | RESEARCH ARTICLE

Cosmic inflation constrains scalar dark matter[1]

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Abstract: In a theory containing scalar fields, a generic consequence is a formation of scalar condensates during cosmic inflation. The displacement of scalar fields out from their vacuum values sets specific initial conditions for post-inflationary dynamics and may lead to significant observational ramifications. In this work, we investigate how these initial conditions affect the generation of dark matter in the class of portal scenarios where the standard model fields feel new physics only through Higgs-mediated couplings. As a representative example, we will consider a Z_2 symmetric scalar singlet s coupled to Higgs via $\lambda \Phi^\dagger \Phi s^2$. This simple extension has interesting consequences as the singlet constitutes a dark matter candidate originating from non-thermal production of singlet particles out from a singlet condensate, leading to a novel interplay between inflationary dynamics and dark matter properties.

Subjects: Astrophysics; Statistical Physics; Theoretical Statistics

Keywords: cosmic inflation; dark matter; Higgs portal

1. Introduction
New physics beyond the standard model of particle physics (SM) is strongly implied by a number of cosmological observations, such as the existence of dark matter and baryon asymmetry in our universe.

Whenever a theory contains scalar fields, such as the SM Higgs boson, which are light and energetically subdominant during cosmic inflation, the inflationary fluctuations generically displace the fields from their vacuum values generating a primordial scalar condensate (Enqvist, Meriniemi, & Nurmi, 2013; Enqvist, Nurmi, Tenkanen, & Tuominen, 2014; Starobinsky & Yokoyama, 1994). These specific out-of-equilibrium initial conditions may then affect physics also at low-energy scales and lead to significant observational ramifications.

ABOUT THE AUTHOR
Tommi Tenkanen is a member of a group which main research activities concentrate on dynamics of quantum fields during and after cosmic inflation, on (p)reheating and on quantum gravity. The connection between standard model Higgs boson and new physics is of particular interest to the group. The research reported in this paper is based on earlier work conducted by the group and its collaborators.

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PUBLIC INTEREST STATEMENT
By studying dynamics of quantum fields in the very early universe, we find a novel connection between the cosmic inflation and dark matter properties. This connection severely constrains some theoretical models which aim to explain the origin of dark matter. The connection also means that the study of gravitational waves may provide an interesting new probe on dark matter properties in the near future.

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In this proceeding, based on Nurmi, Tenkanen, and Tuominen (in press) and first presented in From Higgs to Dark Matter 2014 conference, we investigate how the presence of scalar condensates affect the generation of dark matter in the class of portal scenarios where the standard model fields feel new physics only through Higgs-mediated couplings. As a representative example, we will consider a Z_2 symmetric scalar singlet *s* coupled to Higgs via $\lambda \Phi^\dagger \Phi s^2$.

If the portal coupling takes a value $\lambda \lesssim 10^{-7}$, the singlet *s* never thermalizes with the SM particles and only a so-called freeze-in production of dark matter (Adulpravitchai & Schmidt, 2015; Blennow, Fernandez-Martinez, & Zaldivar, 2014; Hall, Jedamzik, March-Russell, & West, 2010; Hamaguchi, Moroi, & Mukaida, 2012; Klasen, & Yaguna, 2013; McDonald, 2002; Merle, Niro, & Schmidt, 2014; Merle & Schneider, 2014; Yaguna, 2011) is possible. In the standard freeze-in scenario, the dark matter abundance is produced by out-of-equilibrium decay or scattering processes from the thermal bath of particles.

We show that with these values of the portal coupling, it is possible to slowly produce a sizeable fraction of the observed dark matter abundance via singlet condensate fragmentation already at temperatures above the electroweak (EW) scale. This severely constraints the standard freeze-in scenario and requires earlier model computations to be revisited.

2. Field dynamics during and after inflation
The scalar sector of the model is specified by the potential

$$V(\Phi, S) = m_h^2 \Phi^\dagger \Phi + \lambda_h \left(\Phi^\dagger \Phi \right)^2 + \frac{1}{2} m_s^2 s^2 + \frac{\lambda_s}{4} s^4 + \frac{\lambda_{sh}}{2} \left(\Phi^\dagger \Phi \right) s^2 \tag{1}$$

where Φ is the usual standard model Higgs doublet and *s* is a Z_2-symmetric real-singlet scalar. Usually, the exact value of the self-interaction λ_s is considered to be irrelevant for the dark matter production but we shall see that it plays an important role in determining the total dark matter yield.

If the scalar fields are light[2] during cosmic inflation and their energy density is subdominant, the mean fields are subject to acquire large fluctuations around the minima of their potential. Using the so-called stochastic approach (Starobinsky & Yokoyama, 1994), we find that the typical scalar field values at the onset of the post-inflationary era are Enqvist et al. (2014)

$$h_* = \mathcal{O}(0.1) \frac{H_*}{\lambda_h^{1/4}}, \qquad s_* = \mathcal{O}(0.1) \frac{H_*}{\lambda_s^{1/4}} \tag{2}$$

provided that $\lambda_{sh} \lesssim \sqrt{\lambda_s \lambda_h}$. Here H_* is the Hubble parameter value at the end of inflation.

We take the results (2) as inflationary predictions for the initial values of scalar condensates. Assuming an instant reheating, the Higgs acquires a large thermal mass $m_h^2 \simeq 0.1 T^2$ and quickly decays into other SM particles (Enqvist et al., 2014).

As the scalars relax toward their vacuum values, they open up additional channels for the production of singlet particles. As we shall see, these channels may easily compete with the low-energy particle production. In the following, we will concentrate on the regime where the portal coupling take a value $\lambda_{sh} \lesssim 10^{-7}$ and where the singlet never thermalizes above the EW scale.

As the singlet *s* becomes massive, $3\lambda_s s^2 \simeq H$, it starts to oscillate about the minimum of its potential. Ignoring the decay processes, the equation of motion in a flat FRW space reads

$$\ddot{\phi} + 3H\dot{\phi} + V'(s_0) = 0 \tag{3}$$

where $V' \equiv dV/ds$ and s_0 denotes the envelope field value of the homogeneous condensate.

When the singlet oscillates in a $\lambda_s s^4$ potential, the solution to Equation 3 is

$$s_0(T) \simeq 4.9 \times 10^{-3} \lambda_s^{-3/8} \left(\frac{r}{0.1} \right)^{1/4} T \tag{4}$$

where r is the tensor-to-scalar ratio measuring the energy scale of inflation and T is the SM bath temperature.

In a $m_s^2 s^2$ potential, the solution for the envelope reads

$$s_0(T) \simeq 3 \times 10^{-4} \lambda_s^{-5/16} \left(\frac{r}{0.1} \right)^{3/8} \sqrt{\frac{\text{GeV}}{m}} \left(\frac{T}{\text{GeV}} \right)^{3/2} \tag{5}$$

As the singlet oscillates about the minimum of its potential, a transition from the quartic to quadratic regime may take place. This happens approximatively as $3\lambda_s \bar{s}_0^2 \sim m_s^2$, corresponding to

$$T_{\text{trans}} \simeq 200 \lambda_s^{-1/8} \left(\frac{r}{0.1} \right)^{-1/4} m_s \tag{6}$$

If the singlet is light, $m_s \lesssim 0.5\,\text{GeV}$, the potential is essentially given by $\lambda_s s^4$ down to the EW scale.

The dominant decay channel for the singlet condensate is the perturbative production of singlet particles directly from the condensate $s_0(t)$. In the quartic regime, $3\lambda_s s_0^2 \gg m_s^2$, the corresponding singlet particle production rate is given by (see e.g. Ichikawa, Suyama, Takahashi, and Yamaguchi, 2008);

$$\Gamma_{s_0} = 4 \times 10^{-4} \lambda_s^{3/2} s_0 \tag{7}$$

In the quadratic regime, the singlet particle production directly from the condensate is kinematically blocked.

3. Dark matter production

The total number of produced particles can be calculated by writing the effective Boltzmann equation for the number density of singlet particles, n_s,

$$\begin{aligned}
\dot{n}_s + 3Hn_s &= \int dPS_{s_{bg},s,h_1,h_2} |\mathcal{M}|^2_{s_0 h \to sh} f_{s,bg} f_h (1 + f_s)(1 + f_h) \\
&+ \int dPS_{s_{bg},s_1,s_2,s_3} |\mathcal{M}|^2_{s_0 s \to ss} f_{s,bg} f_s (1 + f_s)(1 + f_s) \\
&- \int dPS_{s_{bg},s,h_1,h_2} |\mathcal{M}|^2_{s_0 s \to hh} f_{s,bg} f_s (1 + f_h)(1 + f_h) \\
&+ \Gamma_{s_0} n_{s,bg}
\end{aligned} \tag{8}$$

Here s_0 is the singlet condensate background field value given by Equation 4 in the quartic regime and by Equation 5 in the quadratic regime, Γ_{s_0} is the condensate decay rate given by Equation 7, f_s and f_h are the singlet and Higgs phase space densities, respectively, and $f_{s,bg}$ is the singlet condensate phase space density

$$f_{s,bg} = \begin{cases} \frac{2\pi^3}{\sqrt{3}} \sqrt{\lambda_s} s_0^3 \delta^3(\mathbf{p} = \mathbf{0}), & 3\lambda_s s_0^2 > m_s^2 \\ 4\pi^3 m_s s_0^2 \delta^3(\mathbf{p} = \mathbf{0}), & 3\lambda_s s_0^2 < m_s^2 \end{cases} \tag{9}$$

chosen such that $\rho_{s_0} = m_{s,\text{eff}} n_{s,bg}$. The effective mass $m_{s,\text{eff}}^2$ is equal to $3\lambda_s s_0^2(T)$ in the quartic regime and to m_s^2 in the quadratic part of the potential.

To extract the leading contribution to the total dark matter yield from the condensate, we linearize the Boltzmann Equation (8) in f_s and f_h. The resulting differential equation can be solved exactly. In terms of a yield variable $Y_s \equiv n_s/s_b$, where s_b is entropy density of the SM bath, and temperature T, the solution in the quartic regime is

$$Y_s^{(4)}(T) = \frac{b}{a}\left(e^{a/T} - 1\right) \tag{10}$$

where (in units of GeV)

$$
\begin{aligned}
a &= 3.33 \times 10^{12} \lambda_s^{9/8} \left(\frac{r}{0.1}\right)^{1/4} - 2.40 \times 10^8 \lambda_s^{-5/8} \lambda_{sh}^2 \left(\frac{r}{0.1}\right)^{3/4} \\
b &= \left(5.05 \times 10^5 \lambda_{sh}^2 + 2.58 \times 10^8 \left(\frac{\Gamma_{s_0}}{T}\right)\right) \lambda_s^{-5/8} \left(\frac{r}{0.1}\right)^{3/4}
\end{aligned}
\tag{11}
$$

with the superscript on $Y_s^{(4)}$, we emphasize that the singlet oscillates in the quartic part of its potential.

The corresponding present abundance is

$$\left(\frac{\Omega_s h^2}{0.12}\right) = 2.286 \times 10^9 \left(\frac{m_s}{\text{GeV}}\right) Y_s^{(4)}(T_{EW}) \tag{12}$$

where $T = T_{EW}$ is a natural cut-off for high-temperature processes. Note that the potential is given by $\lambda_s s^4$ down to the EW scale only if $m_s \lesssim 0.5$ GeV.

In the quadratic regime, the solution to Equation 8 can be written as:

$$Y_s^{(2)}(T) = C_1 e^{A/T} - B/A \tag{13}$$

where (in units of GeV)

$$
\begin{aligned}
A &= 5.95 \times 10^8 \left(\lambda_s^2 - \lambda_{sh}^2\right) \lambda_s^{-5/8} \left(\frac{r}{0.1}\right)^{3/4} \\
B &= 3.10 \times 10^8 \lambda_{sh}^2 \lambda_s^{-5/8} \left(\frac{r}{0.1}\right)^{3/4}
\end{aligned}
\tag{14}
$$

and where we fix the coefficient C_1 so that the two solutions, Equations 10 and 13, match at the moment of transition (6). The corresponding present abundance then is

$$\left(\frac{\Omega_s h^2}{0.12}\right) = 2.286 \times 10^9 \left(\frac{m_s}{\text{GeV}}\right) Y_s^{(2)}\left(T_{EW}, Y_s^{(4)}(T_{trans})\right) \tag{15}$$

In order to correctly determine the present DM abundance, one should also take the energy density in the singlet condensate into account. We find that the condensate's contribution to the observed value of DM abundance is given by
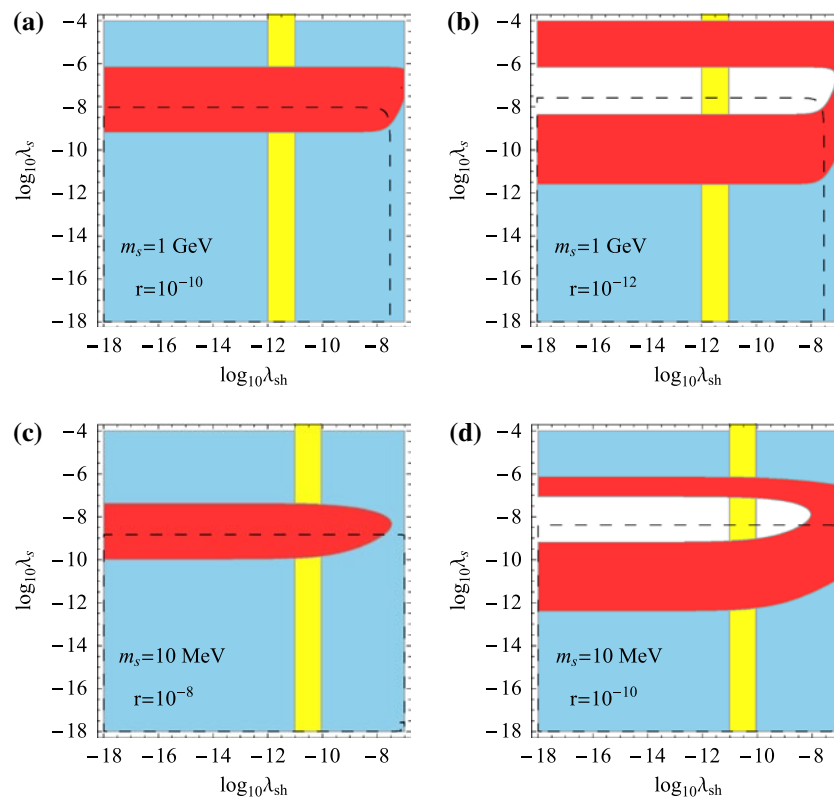
$$\left(\frac{\Omega_s h^2}{0.12}\right) = 10 \lambda_s^{-5/8} \left(\frac{r}{0.1}\right)^{3/4} \left(\frac{m_s}{\text{GeV}}\right) \tag{16}$$

The final dark matter yield above the EW scale is depicted in Figure 1 for different values of m_s and the parameter r. The result severely constrains the viable region where a frozen-in scalar can act as a DM particle.

4. Conclusions

In this work, we have studied the implications of formation of scalar condensates during cosmic inflation. The formation of such condensates is a generic feature of a theory where the scalar fields

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Figure 1. The final dark matter yield above the electroweak (EW) scale in terms of the portal coupling λ_{sh} and the singlet self-coupling λ_s, for different values of m_s and r. Notes: r: the tensor-to-scalar ratio, measuring the energy scale of inflation. The figures are for $m_s = 10$ MeV and $m_s = 1$ GeV, chosen such that the singlet oscillates above the EW scale either in the quartic potential only, or both in the quartic and quadratic regime, respectively. In the deep red region, the singlet condensate and the produced particles constitute 1–100% of today's dark matter (DM) abundance. The light blue region shows a DM overproduction (today's abundance more than 100%). Under the dashed line, the energy of produced s and h particles does not exceed the energy in the singlet condensate. The vertical yellow band shows the standard freeze-in scenario where the low-temperature Higgs decay produces 1–100% of today's DM abundance.

are light and energetically subdominant during inflation, which may have significant consequences on the post-inflationary dynamics.

We have found severe constraints on the freeze-in scenario where the total dark matter abundance is given by presence of a singlet scalar condensate and singlet particles, produced mainly by out-of-equilibrium decay of a singlet condensate. Usually, the energy density of the present remnants of the condensate is the dominant contribution to the observed DM relic density. For the maximum observationally allowed inflationary scale, $r \simeq 0.1$ (BICEP2 Collaboration & Planck Collaboration, 2015), we find that the possibility of a frozen-in scalar as a DM candidate is strictly constrained. We also find that in many cases, the portal coupling λ_{sh} between the singlet scalar and SM Higgs is required to be super-feeble, $\lambda_{sh} \lesssim 10^{-12}$, in order not to produce too much dark matter particles already at high temperatures.

Contrary to the standard freeze-in scenario, the singlet self-coupling λ_s is found to play a crucial role in determination of the correct DM abundance. The result constrains also those models in which the frozen-in scalar acts only as a mediator and decays further to the actual DM particle. For these reasons, all the standard freeze-in scenarios need to be revisited.

The study of formation of scalar condensates and its implications on post-inflationary dynamics has also revealed a novel connection between inflationary dynamics and observed dark matter abundance, meaning that the study of primordial tensor perturbations may provide an interesting new probe on dark matter properties in the near future.[3]

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Citation information
Cite this article as: Cosmic inflation constrains scalar dark matter, Tommi Tenkanen, *Cogent Physics* (2015), 2: 1029845.

Notes
1. This article is associated with the From Higgs to Dark Matter 2014 meeting in Geilo, Norway.

2. The field is defined to be light if $d^2V/ds^2 \equiv m_{s\,\text{eff}} \ll H$ during inflation. This requires roughly $\lambda_s \lesssim 10^{-4}$.

3. For a recent result of a similar notion (see Bhupal Dev, Mazumdar, & Qutub, 2014).

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