Isocurvature Perturbations of Dark Energy and Dark Matter from the Swampland Conjecture

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Abstract. We point out that the recently proposed Swampland conjecture on the potential gradient generically leads to isocurvature perturbations of dark energy, since the quintessence field acquires large quantum fluctuations during high-scale inflation preferred by the conjecture. Also, if the quintessence field is coupled to a dark sector that contains dark matter, isocurvature perturbation of dark matter is similarly induced. Both isocurvature perturbations can be suppressed if the quintessence potential allows a tracker solution in the early Universe. A massive dark photon is an excellent dark matter candidate in this context as its abundance can be explained by quantum fluctuations during inflation without running afoul of isocurvature bounds.
1 Introduction

There have been accumulating observational evidence that supports the existence of an inflationary era in the early Universe. The inflation not only solves various initial condition problems of the standard big bang theory but also explains the origin of density perturbations [1–3]. Also, the current expansion of the universe is accelerating. In the current ΛCDM paradigm, both accelerated cosmic expansions are realized by simple slow-roll inflation and the cosmological constant, respectively. The ΛCDM paradigm is in perfect agreement with the current observations such as the Planck data [4].

The great success of the ΛCDM paradigm plus slow-roll inflation was recently challenged by the so-called Swampland conjectures [5]. The Swampland refers to a set of low-energy theories which look consistent from the low-energy perspective but fail to be UV completed with quantum gravity. One of the conjectures sets a lower bound on the potential gradient as

$$|\nabla V| \geq c,$$  \hspace{1cm} (1.1)

where $c$ is a numerical constant expected to be of order unity, and $V$ is a scalar potential. Here and hereafter, we use the reduced Planck unit: $8\pi G = M_{\text{Pl}}^{-2} = 1$. There are a variety of de Sitter no-go theorem in quantum gravity [6–11] and the conjecture originates with a long history of constructing de Sitter solutions for string theory. The cosmological applications and the validity of the conjecture have been widely discussed and investigated in [5, 12–28].

If applied to the inflaton potential, this conjecture leads to a lower bound on one of the slow-roll parameters, $\varepsilon$, as

$$\varepsilon = \frac{1}{2} \left( \frac{|\nabla V|}{V} \right)^2 \geq \frac{c^2}{2}.$$  \hspace{1cm} (1.2)

As long as the quantum fluctuation of the inflaton is responsible for the observed density perturbation, the $\varepsilon$ parameter is related to the Hubble parameter during inflation as [4]

$$\varepsilon \simeq 0.010 \left( \frac{H_{\text{inf}}}{10^{14} \text{ GeV}} \right)^2.$$  \hspace{1cm} (1.3)
The current bound on $\varepsilon$ comes from non-detection of the primordial gravitational wave. The Planck 95% CL limit on the tensor-to-scalar ratio reads, $r \lesssim 0.10$ [4]. Using the relation of $r = 16\varepsilon$, one obtains

$$\varepsilon \lesssim 0.0063.$$ (1.4)

Under the Swampland conjecture (1.1), this can be expressed as the bound on $c$:

$$c \lesssim 0.11.$$ (1.5)

So, if $c = O(1)$ is taken at a face value, there is already a mild tension between the observation and theoretical expectation [5]. In other words, the Swampland gives a preference to high-scale inflation close to the current bound. Assuming the current bound is saturated, the typical Hubble parameter during inflation is $H_{\text{inf}} \sim 10^{14}$ GeV or so.

Also, the Swampland conjecture (1.1) excludes the cosmological constant as the explanation of the current accelerated expansion, and supports an idea of the quintessence. The quintessence field $\varphi$ slow-rolls on a potential, and its potential energy drives the accelerated cosmic expansion [29–42]. When the conjecture is applied to the current accelerated expansion, the current bound on $c$ reads [5, 43]

$$c \lesssim 0.6.$$ (1.6)

The quintessence field may have interactions with other sectors such as dark matter (DM). However, its couplings to the standard model are subject to the stringent fifth-force constraint, which substantially restricts a possible form of the interaction [5, 52]. In particular, it has been extensively discussed in the literature if the Swampland conjecture is satisfied before the electroweak and QCD phase transitions [53–55]. We do not discuss this issue further. Rather, we focus on implications of the Swampland conjecture for the inflation and the quintessence as they are the main targets of this conjecture. Indeed, one of the striking features of the Swampland conjecture is that it can connect phenomena that took place at vastly different times; both the inflation and the quintessence potentials must satisfy the same simple requirement.

In this Letter we point out that isocurvature perturbation of dark energy (DE) is generically expected from the conjecture. This is the case if the quintessence field remains light and frozen during inflation. Then, it acquires large quantum fluctuations during high-scale inflation preferred by the conjecture, which result in the isocurvature perturbation of DE. If the quintessence field is coupled to a dark sector that contains DM, isocurvature perturbation of DM is similarly induced. We will also argue that vector DM is a good candidate in this context. On the other hand, if the quintessence potential allows a tracker-type solution in the early Universe (e.g. in the case of two exponential terms), the fluctuations of the quintessence field will be significantly suppressed as the late-time dynamics is insensitive to the initial condition.

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Note that the equation-of-state parameter $w_0$ of today is also restricted as $1 + w_0 \geq 0.15c^2$ [5] where $w = \rho/p$ for the dark energy perfect fluid. Currently tension of the Hubble constant $H_0$ between the Planck and the local luminosity distance measurements [44] favors $1 + w < 0$ [45–47], but this lead to the violation of the null energy condition: $\rho + p \geq 0$ [48–50] or the Big Rip singularity [51]. The Swampland conjecture also disfavors this tension [20] and therefore it provides a test for the Swampland itself.
2 Isocurvature perturbations

Let us adopt a simple exponential potential for the quintessence field,

\[ V(\varphi) = \Lambda^4 e^{-c\varphi}, \]  

which saturates the bound (1.6). We expect that the cosmological constant or a constant term in the potential is absent, which may be incompatible to the swampland conjecture. Then the present value of DE should be explained by \( V(\varphi) \).

The dynamics of \( \varphi \) has been extensively studied in the literature (see, e.g., Ref. [5]). It is convenient to define variables \( x \) and \( y \) as

\[ x = \frac{\dot{\varphi}}{\sqrt{6}H} \]  
\[ y = \frac{\sqrt{V(\varphi)}}{\sqrt{3}H^2}. \]

Then the equation of motion is given by

\[ \frac{dx}{dN} = -\frac{\sqrt{6}}{2c}y^2 - 3x + \frac{3}{2}x \left[ (1 - \omega_m)x^2 + (1 + \omega_m)(1 - y^2) \right] \]
\[ \frac{dy}{dN} = \frac{\sqrt{6}}{2c}xy - 3x + \frac{3}{2}y \left[ (1 - \omega_m)x^2 + (1 + \omega_m)(1 - y^2) \right], \]

where \( \omega_m \) is the equation of state of the other components of the Universe. The density parameter and the equation of state are given by

\[ \Omega_{DE} = x^2 + y^2 \]  
\[ \omega = \frac{2x^2}{x^2 + y^2} - 1. \]

When \( \Omega_{DE} \ll 3/c^2 \) in the early Universe, the quintessence field is almost frozen to the initial value. As the Universe expands, the energy density of matter and radiation decreases and that of the quintessence field comes to dominate over them. Its energy density at present can be fine-tuned by adjusting the initial value of \( \varphi_0 \) or \( V(\varphi_0) \). The present value of cosmological constant is many orders of magnitude smaller than the fundamental scale of physics and requires a fine-tuning in the initial condition by a factor of order \( 10^{-120} \). This is known as the cosmological constant problem, which we do not address in this Letter.

Since the quintessence field is extremely light, it acquires quantum fluctuations during inflation:

\[ \delta \varphi = \frac{H_{inf}}{2\pi}. \]

This results in the isocurvature perturbation of DE, which is given by

\[ \left| \frac{\delta \rho_{DE}}{\rho_{DE}} \right| \sim \frac{H_{inf}}{2\pi}, \]

well before it comes to dominate the Universe. The DE isocurvature perturbation evolves afterward until present, but it does not change significantly as long as \( c \) is less than unity.
The effect of DE isocurvature affects the late-time Sachs-Wolfe effects, which appear only at large scales of the CMB anisotropies. Therefore, it is subject to the large uncertainty of the cosmic variance. There is a study on such DE isocurvature perturbations of ultralight axions in a context of the axiverse \cite{56, 57}. According to their analysis, the DE isocurvature bound is much weaker than the DM one, although a dedicated analysis is necessary to derive a rigid constraint.

3 DM interacting with quintessence field

The quintessence field may have couplings to matter fields. While its couplings to the standard model sector are tightly constrained by the fifth force experiments, it is allowed to have sizable couplings to a dark sector which may contain DM. In this Letter, we consider the case where the DM mass could depend on the quintessence field,

$$m_{\text{DM}} \propto e^{-c' \varphi}.$$  \hspace{1cm} (3.1)

3.1 Model-dependent constraints

From the perspective of particle physics, too strong interactions between the light quintessence field and DM are not allowed because of quantum corrections. The interaction induces quantum corrections to the quintessence potential, which may spoil the flatness of the potential. One may require that the one-loop corrections to the effective potential are smaller than the tree level potential. Then we obtain \cite{58}

$$|c'| \lesssim \frac{m_{\varphi}}{\sqrt{Gm_{\text{DM}}^2}} \approx c \frac{H_0}{\sqrt{Gm_{\text{DM}}^2}} \simeq c \left( \frac{1 \text{ meV}}{m_{\text{DM}}} \right)^2.$$  \hspace{1cm} (3.2)

Since we expect $c$ and $c'$ to be of order unity, this requires $m_{\text{DM}} \lesssim 1 \text{ meV}$. This is much smaller than the Tremaine-Gunn phase-space constraint on fermionic DM: $m_{\text{DM}} \gtrsim O(100 \text{ eV})$ \cite{59} (see also Ref. \cite{60}) and therefore the interacting fermionic DM is inconsistent with these considerations.

For the case of bosonic DMs, they can be produced in the early Universe with a large occupancy number, e.g., via the misalignment mechanism, and hence can avoid the phase-space constraint. A well-motivated DM model of this kind is an axion-like particle, where its tiny mass is generated by a non-perturbative effect and a sizable energy density can be produced via the misalignment mechanism. However, since its mass is quite small, it acquires quantum fluctuations during inflation. This leads to isocurvature perturbations for DM, which is severely constrained by the Planck collaboration as we discussed above. Although it is difficult and non-trivial, several mechanisms are proposed to suppress its fluctuations by, e.g., making the axion-like particle massive temporarily during inflation \cite{61–77}.

An interesting possibility is that the DM is a massive vector field $A_\mu$. The longitudinal modes are produced by quantum fluctuations during inflation and the resulting spectrum is suppressed on large scales. This leads to a suppression of isocurvature modes and a correct adiabatic fluctuation spectrum. The abundance of vector field is calculated as \cite{78}

$$\Omega_{\text{DM}} h^2 \simeq 0.1 \left( \frac{m_{\text{DM}}}{6 \text{ meV}} \right)^{1/2} \left( \frac{H_{\text{inf}}}{10^{14} \text{ GeV}} \right)^2.$$  \hspace{1cm} (3.3)
This is consistent with the fact that the swampland conjecture favours the large-scale inflation (1.3) and the constraint of quantum corrections to the quintessence potential (3.2).

### 3.2 Model-independent constraints

Now we shall consider constraints that arise independently on the nature of DM.

The coupled system of DM and DE is subject to various cosmological observations. The quintessence field mediates interactions between DMs, whose strength has an upper bound from the fifth-force constraint on DM [80, 81] (more references may be needed). It reads

\[ |c'| \lesssim 0.3. \tag{3.4} \]

However, this can be avoided if the quintessence field is pseudo-scalar and couples with DM only via spin-dependent interactions.

The DM mass is time-dependent because of the interaction with the quintessence field. When \( c' \) is positive, the mass starts to decrease around the time when the cosmic expansion gets accelerated. This is similar to the decaying DM scenario as the gravitational potential decays, but it is different because the evolution is correlated with DE. The detailed analysis of the system is beyond the scope of this Letter, and further analysis is warranted. Here we simply require that the DM mass should not change by a factor of 10% after the matter-dominated epoch, which was found by investigating amplitude of matter fluctuations \( \sigma_8 \) in the decaying DM model [82]. The quintessence field varies by a factor of

\[ \Delta \varphi = \int_{N_{eq}}^{N_p} \sqrt{6} \times dN \simeq 0.18, \tag{3.5} \]

after the matter-dominated epoch, where \( N_p \) and \( N_{eq} \) represent the e-folding numbers at present and at the matter-radiation equality, respectively. Thus we obtain

\[ c' \lesssim 13, \tag{3.6} \]

from the constraint on the variation of the energy density of DM after the matter-radiation equality. The fact that the upper bound on \( c' \) derived above is rather weak implies that the time-evolution of DM mass has a negligibly small impact on observations.

If \( c' \) is negative, the DM mass starts to increase around the time when the cosmic expansion gets accelerated. In this case, the amplitude of matter fluctuations gets enhanced because of deeper gravitational potential of DM. Here, we note that the amplitude of matter fluctuation \( \sigma_8 \) observed by a large scale structure is slightly smaller than that indicated by the CMB measurement [4]. The negative \( c' \) predicts a larger \( \sigma_8 \) at present epoch, which would strengthen the discrepancy between the observations of large scale structure and CMB. On the other hand, if a subdominant component of DM interacts with the quintessence field, negative \( c' \) has an interesting cosmological scenario (see, e.g., Refs. [83, 83–86]).

The isocurvature perturbations of DM are induced by the interaction with the quintessence field via the fluctuation \( \delta \varphi = H_{\text{inf}}/(2\pi) \) as

\[ \frac{\delta \rho_{DM}}{\rho_{DM}} = \frac{\delta m_{DM}}{m_{DM}} = |c'| \frac{H_{\text{inf}}}{2\pi}. \tag{3.7} \]

\[ ^2 \text{The abundance can be given by Eq. (3.3) only if its tiny mass is already turned on during inflation. This can be realized when the vector field has a Stueckelberg mass. However, a new conjecture was proposed in Ref. [79], where they show that the Stueckelberg mass cannot be smaller than a certain threshold depending on a cutoff of the theory. If we take the cutoff to be larger than } H_{\text{inf}}, \text{ the Stueckelberg mass need to be less than } 0.3 \text{ eV according to this new conjecture.} \]
The Planck observations set a tight bound on the uncorrelated DM isocurvature as \[ \beta_{\text{iso}} \equiv \frac{P_{II}}{P_{RR} + P_{II}} < 0.038 \ (95\% \ CL), \] where \( \beta_{\text{iso}} \) is the ratio of the isocurvature power spectrum to the total (adiabatic \( P_{RR} \) plus isocurvature \( P_{II} \)) power spectrum. This leads to the bound on \( c' \):

\[ |c'| < 1.4 \left( \frac{10^{14} \text{ GeV}}{H_{\text{inf}}} \right). \] (3.9)

Note that this bound on \( c \) is complementary to the one derived by non-observation of the primordial gravitational waves (1.5). For a smaller value of \( H_{\text{inf}} \), the former becomes weaker while the latter gets tighter. These isocurvature perturbations come from the fluctuation of the quintessence field, so that they are independent of the isocurvature modes of the fluctuation of DM itself that are discussed in Sec. 3.1.

4 Discussion and conclusions

The constraint from the isocurvature perturbations can be avoided by introducing another exponential term in the quintessence potential with a large coefficient in the exponent, such as \[ V(\varphi) = \Lambda_1^4 e^{-c_1 \varphi} + \Lambda_2^4 e^{-c_2 \varphi}. \] When \( c_2 \gg 1 \), the field \( \varphi \) has an attractor solution with the density parameter \( \Omega_{\text{DE}} = 3/c_2^2 \), which removes the dependence of the DE on the initial condition [88]. In this case the primordial fluctuation of \( \varphi \) does not affect the present value of DE and the isocurvature perturbations are absent [89–91]. The fine-tuning of DE at the present value is realized by the fine-tuning of parameters in its potential.

In this Letter we have applied the Swampland conjecture on the potential gradient to both inflation and quintessence, and studied its implication for isocurvature perturbations of DE and DM. In particular, if \( c = O(1) \) is taken at face value, it gives a preference to high-scale inflation which almost saturates the current upper bound on the tensor-to-scalar ratio. For such high-scale inflation, the quintessence field generically acquire large quantum fluctuations during inflation, which may results in isocurvature perturbation of DE. However, the current bound on isocurvature perturbation of DE is rather weak and does not give a meaningful bound on \( c \).

We also studied the case in which the quintessence field is coupled to the mass term of DM. In this case, CDM isocurvature perturbation is similarly induced. Also, the DM mass should be smaller than meV to avoid producing too large radiative corrections to the quintessence potential. This excludes a possibility of fermionic DM. Among bosonic DM candidates, we find that a massive dark photon is an excellent candidate since it is naturally produced by quantum fluctuations during inflation, while isocurvature perturbations on large scales are suppressed. For the high-scale inflation with \( H_{\text{inf}} = 10^{14} \text{ GeV} \), the right relic abundance is realized for \( m_{\text{DM}} \sim 6 \mu eV \) which satisfies the above requirement. The vector DM has been an active target of various proposed experiments [92–97].

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