Minimal gauge inflation and the refined Swampland conjecture

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Abstract. The refined de Sitter (dS) conjecture provides two consistency conditions for an effective theory potential of a quantum gravity theory. Any inflationary model can be checked by these conditions and minimal gauge inflation is not an exception. We develop a generic method to analyze a monotonically growing potential with an inflection point on the way to the plateau near the top such as the potential in minimal gauge inflation model and the Higgs inflation. Taking the latest observational data into account, we find the fully consistent parameter space where the model resides in the Landscape rather than in the Swampland.

Keywords: cosmology of theories beyond the SM, extra dimensions, inflation

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1 Introduction

The refined de Sitter (dS) conjecture, the latest version of the Swampland conjecture, was recently proposed by Ooguri, Palti, Shiu and Vafa [1], also earlier by Garg and Krishnan [2] after an earlier version proposed by Obied, Ooguri, Spondyneikeo and Vafa [3]. The conjecture states that any scalar potential $V(\phi)$ for scalar fields in a low energy effective theory of a consistent quantum gravity must satisfy at least one of the following conditions:

\begin{align}
||\nabla V|| &\geq c_1 \frac{V}{M_P} , \quad \text{(Condition-1)} \\
\min(\nabla_i \nabla_j V) &\leq -c_2 \frac{V}{M_P^2} , \quad \text{(Condition-2)}
\end{align}

where $c_1$ and $c_2$ are universal, positive constants of order unity and $\min(\nabla_i \nabla_j V)$ of the second condition is the minimum eigenvalue of the Hessian $\nabla_i \nabla_j V$ in an orthonormal frame.\footnote{In literatures, $c$ and $c'$ are also widely used instead of $c_1$ and $c_2$ in this paper. Note $c_1$ and $c_2$ are for the first and the second derivatives of the potential, respectively.}

One of the most straightforward and intriguing implications of the conjecture is that the cosmological constant scenario, for which $||\nabla V_{c.c}|| = 0$ and $V_{c.c.} > 0$, is ruled out but the quintessence field with an exponentially decaying potential $V_Q(Q) = \Lambda_Q^4 e^{-c_Q Q}$ would consistently explain the late time expansion if $c_Q \geq c_1$ (see a recent review of quintessence model [4]). There have been many follow-up papers considering various implications of the conjecture [5–29].

Distinctively from the (Condition-1), the newly added (Condition-2) is rather easily satisfied for a generic potential in low scale, $\Delta \phi \ll M_P$, because

\begin{equation}
M_P^2 \frac{\nabla_i \nabla_j V}{V} \sim -\frac{M_P^2}{\Delta \phi^2} \ll -c_2 \sim -O(1) .
\end{equation}

However, inflationary dynamics, which takes place at a high scale, is constrained by the conditions as analyzed recently in ref. [6] (see e.g. [30] in supergravity.). The dS conjecture indeed provides some new insights in viewing each model so that we are motivated to examine...
a new kind of model, which has not been examined so far: a minimal gauge inflation model introduced in ref. [31].

In the next section, section 2, we start from the inflaton potential of minimal gauge inflation model and apply the dS conjecture to read out the consistency conditions in generic field space. In section 3, now considering the latest cosmological observations from the Planck 2018 and also the polarization measurements from BICEP/Keck, we re-examine the dS conditions for a fully realistic case, which can provide the most interesting understanding of the model in light of the dS conjecture. Finally we conclude in section 4.

2 Minimal gauge inflation and the Conditions of refined Swampland conjecture

A minimal gauge inflation model is based on a higher dimensional theory of non-Abelian SU(2) gauge symmetry on the orbifold, $S^2/Z_2$ [31] with only a few free parameters, the compactification radius, $R$, and the gauge coupling constant, $g_5$ in five dimensions. The model is supposed to be the simplest realization of this category [32–35]. The inflaton is identified with the extra dimensional component of the gauge field, $A_5 \sim \phi$, and its potential is protected by the higher dimensional gauge symmetry itself but generated at one-loop level by gauge self interactions. As a result, the model is extremely predictive. It is desired to check if this model is consistent with the refined dS conjecture.

The inflaton potential of minimal gauge inflation model is

$$V(\phi) = V_0 \sum_{n=1}^{\infty} \frac{1}{n^5} \left[ 1 - \cos \frac{n\phi}{f_{\text{eff}}} \right]$$

$$= -\frac{V_0}{2} \left[ \text{Li}_5(e^{i\phi/f_{\text{eff}}}) + \text{Li}_5(e^{-i\phi/f_{\text{eff}}}) - 2\zeta(5) \right],$$

where two of the most important model parameters, $V_0$ and $f_{\text{eff}}$, are introduced: $V_0 = \frac{9}{(2\pi)^3 R^4}$ is the scale of the potential and $f_{\text{eff}} = \frac{1}{\sqrt{2\pi g_5 R}} = \frac{1}{2\pi g_4 R}$ is the ‘effective decay constant’. The

\[2\] In ref. [36], the electroweak symmetry breaking is realized by a fully radiatively generated potential.
potential is composed of infinitely many periodic terms. It has a maximum at $\phi/f_{\text{eff}} = \pi$ and we only consider the physical region in $\phi/f_{\text{eff}} = (0, \pi)$. The inflation starts below $\phi/f_{\text{eff}} \approx \pi$ then roll-down to the true vacuum at $\phi/f_{\text{eff}} = 0$. The model may be regarded as a UV completion of the natural inflation models [37–39]. The shape of the potential is depicted in figure 1.

2.1 Condition-1

We first request (Condition-1) or $M_P||V'||/V \geq c_1$. A convenient function is introduced:

$$C\left(\frac{\phi}{f_{\text{eff}}}\right) \equiv f_{\text{eff}} \frac{||V'||}{V} \geq c_1 \quad (2.2)$$

$$= \frac{i \left[ \text{Li}_4(e^{-i\phi/f_{\text{eff}}}) - \text{Li}_4(e^{i\phi/f_{\text{eff}}}) \right]}{\text{Li}_5(e^{i\phi/f_{\text{eff}}}) + \text{Li}_5(e^{-i\phi/f_{\text{eff}}}) - 2\zeta(5)} \quad (2.3)$$

The function is plotted in figure 2 (upper curve). As the function is monotonically decreasing within the range of our interest, (Condition-1) sets up an upper limit for $\phi$:

$$C\left(\frac{\phi}{f_{\text{eff}}}\right) \geq c_1 \frac{f_{\text{eff}}}{M_P} \Leftrightarrow \phi \leq \phi_* = f_{\text{eff}} C^{-1}\left(c_1 \frac{f_{\text{eff}}}{M_P}\right). \quad (2.4)$$

The critical value, $\phi_*$, is determined for a given value of $c_1f_{\text{eff}}/M_P$. In principle, the parameter is constrained by the inflationary observables. We will be discuss this in section 3.

2.2 Condition-2

The potential is convex ($V'' > 0$) for a small field value of $\phi/f_{\text{eff}}$ then becomes concave ($V'' < 0$) toward the plateau located at the top. The inflection point ($V'' = 0$) locates at $\phi/f_{\text{eff}} \approx 1.45$. To analyze the second condition, we introduce a convenient function, $D$, which encapsulates the information of the curvature of the potential:

$$D\left(\frac{\phi}{f_{\text{eff}}}\right) \equiv f_{\text{eff}}^2 \frac{V''}{V} \quad (2.5)$$

$$= -\frac{\text{Li}_3(e^{-i\phi/f_{\text{eff}}}) + \text{Li}_3(e^{i\phi/f_{\text{eff}}})}{\text{Li}_5(e^{i\phi/f_{\text{eff}}}) + \text{Li}_5(e^{-i\phi/f_{\text{eff}}}) - 2\zeta(5)}. \quad (2.6)$$

The shape of the $D$ is depicted in figure 2 (lower curve).
The function is monotonically decreasing and (Condition-2) limits the validity range of \( \phi \) and sets the lower bound \( \phi^* \) as
\[
D \left( \frac{\phi}{f_{\text{eff}}} \right) \leq -c_2 \frac{f_{\text{eff}}^2}{M_P^2} \iff \phi \geq \phi^* = f_{\text{eff}} D^{-1} \left( -c_2 \frac{f_{\text{eff}}^2}{M_P^2} \right) .
\]

(2.7)

### 2.3 Condition-1 and Condition-2

In principle, (Condition-1) in eq. (2.4) and (Condition-2) in eq. (2.7) are independent. However, at least one of the conditions can be satisfied in the whole region of \( \phi \) if the lower bound of (Condition-2), \( \phi^* \), is smaller than the upper bound of (Condition-1), \( \phi^* \) or
\[
\frac{\phi^*}{f_{\text{eff}}} = D^{-1} \left( -c_2 \frac{f_{\text{eff}}^2}{M_P^2} \right) \leq C^{-1} \left( c_1 \frac{f_{\text{eff}}}{M_P} \right) = \frac{\phi^*}{f_{\text{eff}}} .
\]

(2.8)

This inequality is a generic condition that should be taken as the guiding principle of a model, which has similar features: growing potential having an inflection point in the middle toward the top of the potential. There are many examples of this kind including the Higgs inflation [40–45].

If the above condition is not satisfied, there exists a region of \( \phi \in (\phi^*, \phi^*) \) where neither condition is satisfied. Indeed, as one can notice in the figure, \( C \gtrsim D \) in \( f/f_{\text{eff}} \gtrsim \pi/4 \) so that one can actually find a set of values \((c_1, c_2)\) for a given value of \( f_{\text{eff}}/M_P \) satisfying the desired condition as one can clearly see in figure 2. For instance, with \((c_1, c_2) = (0.3, 0.1)\) and \( f_{\text{eff}}/M_P \approx 1.2 \), \((\phi^*, \phi^*) \approx (1.6 f_{\text{eff}}, 2.4 f_{\text{eff}})\) thus the dS criterion is satisfied.

In figure 3 we depicted the critical lines in the plane of \((c_1, c_2)\) for various values of \( f_{\text{eff}}\):
\[
f_{\text{eff}}/M_P = 0.9, 1.0, 1.1, 1.2 .
\]

The regions below the lines (colored parts), the critical condition, \( \phi^* \leq \phi^* \), is satisfied thus the condition of the refined dS conjecture is fulfilled and belongs to the “Landscape” but in the regions above the lines, the potential may not have a consistent quantum gravitational UV completion or belongs to the “Swampland”.

Until this far, we examined the implications of the refined dS conjecture to generic field space of minimal gauge inflation model. Using the method, we found that the allowed range of \((c_1, c_2)\) depends on \( f_{\text{eff}}\). On the other hand, if \((c_1, c_2)\) are known a priori, we can set the theoretically preferred range of the model parameters. Instead, in this paper, we take the observational data as the guideline of a theory and try to set the bound on \((c_1, c_2)\) in the next section.

Before going further, we comment on the excursion of the field \( \Delta \phi \) over the inflation. When we replace the derivative of the potential by the ratio of differences \( \Delta V/\Delta \phi \), the first condition (C1) implies
\[
\frac{\Delta V}{\Delta \phi} \gtrsim c_1 \frac{V}{M_P} \Rightarrow \frac{\Delta \phi}{M_P} \lesssim \frac{1}{c_1} \frac{\Delta V}{V} < \frac{1}{c_1} ,
\]

(2.9)

for the change of the potential \( \Delta V < V \). The excluded region by this condition or equivalently by (C1) in our case is \( \phi > \phi^* \) (see figure 2). However, as it is emphasized in the refined Swampland conjecture [1, 2], larger possibilities are allowed by the second condition since \( \phi > \phi^* \) satisfies (C2).
3 Inflationary predictions

The inflationary observables, the power spectrum of the curvature perturbation, $\mathcal{P}_\zeta$, the corresponding spectral index, $n_s$, the tensor-to-scalar ratio, $r$, of minimal gauge inflation are obtained in ref. [31]:

$$\mathcal{P}_\zeta \approx \frac{V_0 f_{\text{eff}}^2}{6\pi^2 M_P^6} e^{-N_e M_P^2/f_{\text{eff}}^2},$$  \hspace{1cm} (3.1)$$

$$n_s \approx 1 - \frac{M_P^2}{f_{\text{eff}}^2},$$  \hspace{1cm} (3.2)$$

$$r \approx 8 \frac{M_P^2}{f_{\text{eff}}^2} e^{-N_e M_P^2/f_{\text{eff}}^2},$$  \hspace{1cm} (3.3)$$

where $N_e$ is the number of efolds. From these, we get the model parameters and $N_e$ as

$$V_0 \approx \frac{48\pi^2 \mathcal{P}_\zeta (1 - n_s)^2}{r M_P^4},$$  \hspace{1cm} (3.4)$$

$$f_{\text{eff}} \approx \frac{1}{\sqrt{1 - n_s}} M_P,$$  \hspace{1cm} (3.5)$$

$$N_e \approx \frac{1}{1 - n_s} \log \frac{8(1 - n_s)}{r}.$$  \hspace{1cm} (3.6)$$

We take the reference values

$$\mathcal{P}_\zeta = 2.5 \times 10^{-9}, n_s = 0.965 \pm 0.004,$$  \hspace{1cm} (3.7)$$

from the recent data of Cosmic Microwave Background radiation (CMB) from the Planck observatory [46–48] and also the data taken by the BICEP2/Keck CMB polarization experiments [49] then we determine the model parameters, $V_0$ and $f_{\text{eff}}$, as well as the allowed window for $r$ as

$$V_0 \big|_{\text{Planck+BICEP2+Keck}} \approx (3.0 - 4.2) \times 10^{-8} M_P^4,$$  \hspace{1cm} (3.8)$$

$$f_{\text{eff}} \big|_{\text{Planck+BICEP2+Keck}} \approx 5.3 M_P,$$  \hspace{1cm} (3.9)$$

$$r \big|_{\text{Planck+BICEP2+Keck}} \approx 0.034 - 0.049.$$  \hspace{1cm} (3.10)$$

Figure 3. The critical line of $(c_1, c_2)$. The region above the line is excluded by the dS conjecture or belongs to the “Swampland”.

\[\text{Diagram with critical lines and labels}\]
for the requested number of efolds, $N_e = 50 - 60$. Notice that the tensor-to-scalar ratio $r$ is within the future probe. The determined values of $V_0$ and $f_{\text{eff}}$ would give the compactification radius and the gauge coupling constant:

$$R M_P \approx 7.7 - 8.4,$$

$$g_4 \approx (3.5 - 3.9) \times 10^{-3},$$

which look consistent with the quantum gravity and the perturbative gauge theory with $g_4 \ll 4\pi$.

Finally, having determined the input parameters of the model we now can directly check the dS conjecture. The figure 4 is depicted to show the parametric region of $(c_1, c_2)$ which is consistent with the dS conjecture as well as the observational data. The allowed values of $c_1$ and $c_2$ are typically $c_1 \sim 0.15$ and $c_2 \sim 0.01$ or smaller. The values are not strictly $O(1)$ as requested in the conjecture but still close numerically.

4 Conclusion

The latest swampland conjecture could provide important implications to the low energy effective theory models which may or may not be consistent with the quantum gravity theory. The conjecture suggests two related but independent conditions for any scalar potential $V(\phi)$ of a low energy effective theory of a consistent quantum gravity:

$$||\nabla V|| \geq c_1 \frac{V}{M_P}, \quad \min(\nabla_i \nabla_j V) \leq -c_2 \frac{V}{M_P^2},$$

which we call (Condition-1) and (Condition-2), respectively, in this paper. The parameters $c_1$ and $c_2$ are supposed to be universal but unknown positive constants. In this paper, we closely examine a minimal gauge inflation model as a concrete example of potentially realistic inflationary model and apply the dS conjecture to see the consistency with a quantum gravity theory. Interestingly, the potential indeed allows a parametric region in $(c_1 \lesssim 1, c_2 \lesssim 1)$. If we apply the latest cosmological observations from Planck 2018 and also BICEP2+Keck, the allowed region shrinks but still exists as is clearly seen in figure 4. We also would emphasize that the method developed in this paper can be applied to any theory with a similarly behaving potential: growing monotonically, having an inflection point on the way to the top.
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