High-scale SUSY from an R-invariant New Inflation in the Landscape

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Abstract

We provide an anthropic reason that the supersymmetry breaking scale is much higher than the electroweak scale as indicated by the null result of collider experiments and observed 125 GeV Higgs boson. We focus on a new inflation model as a typical low-scale inflation model that may be expected in the string landscape. In this model, the R-symmetry is broken at the minimum of the inflaton potential and its breaking scale is related to the reheating temperature. Once we admit that the anthropic principle requires thermal leptogenesis, we obtain a lower bound on gravitino mass, which is related to R-symmetry breaking scale. This scenario and resulting gravitino mass predict the consistent amplitude of density perturbations. We also find that string axions and saxions are consistently implemented in this scenario.
1 Introduction

The observed 125 GeV Higgs boson [1, 2] and the null result of supersymmetric (SUSY) particles at the LHC may imply that the SUSY breaking scale is much higher than the electroweak scale [3, 4, 5]. This seems to be unnatural in light of the (little) hierarchy problem, which would compel one to search for the reason that the nature “selects” such a large SUSY breaking scale. In this paper we provide its cosmological reason in the anthropic landscape.

The string landscape indicates that there are a lot of local vacua with different values of potential energy, which implies that universes can have any values of cosmological constant [6, 7, 8, 9]. In the anthropic landscape, it is argued that we cannot live in a universe with a larger cosmological constant than the observed value or with a negative one, so that our universe is the one with a marginal value of cosmological constant, which is consistent with the observation [10] (see also Ref. [11, 12]). This may be a unique solution to the cosmological constant problem in our present understanding, so that in this paper we stand on this scenario.

Low-scale inflation may be a natural consequence of the anthropic landscape, where inflations occur at infinitely many vacua. Old inflation occurs at a local vacuum and it ends via the tunnelling to a vacuum with a smaller vacuum energy. Then inflation may continue at that vacuum. Eventually, the inflaton tunnels into a vacuum around which observable slow-roll inflation occurs. This scenario implies that the observable inflation is that with a relatively small energy scale. Among simple inflation models in supersymmetry (SUSY), including chaotic inflation [13, 14] and hybrid inflation models [15, 16], new inflation models are one class of the simplest and smallest-energy scale inflation models [17, 18, 19, 20]. Therefore, in this paper, we focus on the new inflation model considered in Refs. [17, 20]. In this model, R-symmetry is broken at the global minimum and gravitino mass depends on parameters in the inflaton sector. As a result, the upper-bound on reheating temperature is related to the gravitino mass. We find that the gravitino mass needs to be larger than of order 100 TeV in order to realize the thermal leptogenesis [21], which may be required by the anthropic principle. This is the reason that the SUSY breaking scale is much higher than the electroweak scale as indicated by the collider experiments.

The gravitino with mass of 100 TeV is consistent with the other observations and constraints in the anthropic landscape. First, the observed amplitude of density perturbations is a natural consequence of our model with 100 TeV gravitino mass. Secondly, string axions [22, 23, 24, 25, 26, 27], whose decay constants are of order the grand unified theory (GUT) scale, can be consistently introduced in our scenario. Their initial amplitudes are
fine-tuned not to overclose the Universe in the anthropic landscape, while the constraint on axion isocurvature perturbation is avoided due to the low-energy nature of new inflation [28, 29, 30, 31, 32, 33]. In the anthropic landscape, the lightest SUSY particle (LSP) overproduction problem by saxion decay is also avoided by fine-tunings of saxion initial amplitudes, where we assume R-parity conservation. This implies that the saxion decay does not produce much entropy, so that the thermal leptogenesis can be realized consistently. The saxion, whose mass is about gravitino mass of order 100 TeV, safely decays into radiation before the Big Bang nucleosynthesis (BBN) epoch, which is required by the consistency of our scenario with the BBN theory [34]. Finally, the gravitino problem is also alleviated by 100 TeV gravitino mass because such a heavy gravitino safely decays before the BBN epoch. The thermal relic of the LSP is not overabundant when the LSP is wino or higgsino with a mass less than $O(1)$ TeV [35] (see also Refs. [36]),¹ which is naturally realized in pure gravity mediation [38, 39].² In this case, the produced LSP from gravitino decay does not overclose the Universe for reheating temperature of order $10^9$ GeV.

Here we summarize our standing point in this paper.

1. Anthropic landscape:

   The cosmological constant problem is solved by the anthropic principle. We consider a new inflation model that may be favoured in the string landscape.

2. Thermal leptogenesis:

   The observed baryon asymmetry is generated by the thermal leptogenesis. As a result, 100 TeV gravitino mass is predicted in the anthropic landscape.

3. String axions:

   The strong CP problem is solved by the PQ mechanism. The dark matter (DM) overproduction problems from axion oscillations and saxion decays are avoided by fine-tunings of their initial amplitude in the anthropic landscape.

This paper is organized as follows. In the next section, we consider the new inflation model with R-symmetry breaking at the potential minimum. We discuss the reheating process and explain that the thermal leptogenesis can be realized only for gravitino mass of order 100 TeV. Then we derive a condition to the realization of eternal inflation in new inflation, which may provide a reason of smallness of a parameter in Kähler potential. In

¹ See an early work [37].
² For a similar model, see Ref. [40].
Sec. 3, we explain axion and saxion cosmology and discuss consistency of our scenario with string axions. Section 4 is devoted to conclusion.

2 New inflation

If many inflations occur in the string landscape, it is natural to consider that the observable inflation is the one with the smallest energy scale. Thus we consider a new inflation model, which is one of the simplest and smallest-energy scale inflation models among inflation models in SUSY.

2.1 Model

We consider the new inflation model in supergravity that is realized by the following superpotential [17]:

\[ W = v^2 \phi - \frac{g}{6} \phi^6, \]

where \( v \) and \( g \) are parameters and can be taken to be real positive by \( U(1)_R \) rotation and field redefinition without loss of generality. Here we implicitly assume \( Z_{10R} \) symmetry.\(^3\) We use the Planck unit where the reduced Planck scale \(( \simeq 2.4 \times 10^{18} \text{ GeV})\) is identified with unity. We consider a Kähler potential of

\[ K = |\phi|^2 + \frac{k}{4} |\phi|^4, \]

where \( k \) is a real parameter. One might naively expect that \( k \) is of order unity, but for a moment we take it as a free parameter. In supergravity, the potential of \( \phi \) is written as

\[ V_{\text{new}} = v^4 - kv^4 |\phi|^2 - gv^2 (\phi^5 + \phi^5) + g^2 |\phi|^{10} + \ldots, \]

where we assume \( v^2 \ll 1 \) and neglect higher-dimensional terms. At the minimum of the potential, the VEV of the inflaton \( \phi \) is given by

\[ \langle \phi \rangle_{\text{min}} \simeq \left( \frac{v^2}{g} \right)^{1/5}, \]

and the \( Z_{10R} \) symmetry is broken down to the R-parity \( Z_{2R} \). Note that SUSY is not broken at the minimum of the potential while the superpotential has a nonzero value of

\[ \langle W \rangle_{\text{min}} \simeq \frac{5}{6} v^2 \left( \frac{v^2}{g} \right)^{1/5}, \]

\(^3\) A model with \( Z_{6R} \) symmetry predicts too red-tilted spectral index compared with the observed value [20]. It is an open question why the nature respects \( Z_{10R} \) symmetry.
so that gravitino obtains a mass of $m_{3/2} = e^{(K)/2} \langle W \rangle_{\text{min}} \approx \langle W \rangle_{\text{min}}$.

The properties and predictions of this new inflation model has been investigated in detail in Ref. [20]. Here we quote their results. The spectral index can be within the observed value (i.e., $n_s = [0.952, 0.976]$) for

$$k = [10^{-2.6}, 10^{-1.7}].$$

(6)

We obtain the observed amplitude of the curvature perturbations $\mathcal{P}_\zeta \approx 2.2 \times 10^{-9}$ when $v$ is given by

$$v \approx 1.1 \times 10^{13} \text{ GeV} \left(\frac{g}{1000}\right)^{-1/4},$$

(7)

where we assume $k = 0.01$ and the $e$-folding number to be 50. In the next section, we predict $v$ of order this value in the anthropic landscape. Equation (7) implies the energy scale of inflation as

$$H_{\text{new}} \approx 10^7 \text{ GeV},$$

(8)

and the gravitino mass of

$$m_{3/2} \approx \frac{5g}{6} \left(\frac{v^2}{g}\right)^{6/5} \approx 8.0 \times 10^4 \text{ GeV} \left(\frac{g}{1000}\right)^{-4/5}.$$

(9)

We expect that the gravitino mass should be as small as possible so that fine-tunings of electroweak scale and cosmological constant are as small as possible. Thus we take the largest possible $g$. A large coupling constant $g$ leads to a large radiative correction to the Kähler potential. Counting the number of loops and symmetry factors, we estimate the radiative correction such as

$$\delta K \sim \frac{5!}{(16\pi^2)^4} g^2 M_{\text{Pl}}^6 |\phi|^2 + \frac{4!}{(16\pi^2)^3} g^2 M_{\text{Pl}}^4 |\phi|^4 + \ldots,$$

(10)

where we assume the cutoff scale to be the Planck scale and explicitly write it as $M_{\text{Pl}}$. The unitarity limit $|\delta K| \lesssim |\phi|^2$ leads to an upper bound on $g$ as $g \lesssim 2000$. Note that this is consistent with the naive dimensional analysis. Hereafter we take $g \sim 1000$ and then the gravitino mass is of order 100 TeV. Note that the parameter $k$ in the Kähler potential of Eq. (2) is as large as 100 due to the radiative correction. This implies that there is a fine-tuning of order 0.01% in the Kähler potential for the spectral index to be consistent with the observed value. In Sec. 2.4, we provide a scenario to explain this fine-tuning.
|   | $5^*$ | $10$ | $H_u$ | $H_d$ | $N$ | $\phi$ | $Q(5)$ | $Q(5^*)$ |
|---|---|---|---|---|---|---|---|---|
| $Z_{10R}$ | 1 | 1 | 0 | 0 | 1 | 2 | 5 | 1 |
| $U(1)_{B-L}$ | −3 | 1 | −2 | 2 | 5 | 0 | 3 | −3 |

Table 1: Charge assignment for matter fields.

### 2.2 Thermal leptogenesis and high-scale SUSY

Here we discuss the reheating process after the new inflation. We introduce additional GUT multiplets $Q$ and $\bar{Q}$ and assign R-charges and $U(1)^B_L$ charges as shown in Table 1, where $5^*$ and $10$ are Minimal SUSY Standard Model (MSSM) GUT multiplets and $N$ is the right-handed neutrino. Then we can write the superpotential of

$$W_{\text{decay}} = \frac{y}{3} \phi^3 Q\bar{Q} + y'\bar{Q}10H_d.$$  \hfill (11)

The first term leads to the decay of the inflaton into $Q$ and $\bar{Q}$ while the second one allows $Q$ and $\bar{Q}$ to decay into MSSM particles subsequently. Note that since the potential minimum is found to be Eq. (4) and $\langle Q \rangle = \langle \bar{Q} \rangle = 0$ in this model, the above superpotential does not affect the scenario of the new inflation.

The effective mass of $Q$ and $\bar{Q}$ at the global minimum is given by

$$m_Q = \frac{y}{3} \langle \phi \rangle^3$$ \hfill (12)

$$\simeq \frac{y}{3} \left(\frac{v^2}{g}\right)^{3/5},$$ \hfill (13)

while the mass of the inflaton is given by

$$m_\phi \simeq 5g \left(\frac{v^2}{g}\right)^{4/5}.$$ \hfill (14)

We require $m_\phi \geq 2m_Q$ so that the inflaton can decay into $Q$ and $\bar{Q}$. The decay rate is then estimated as

$$\Gamma_\phi \simeq \frac{5}{8\pi} y^2 \langle \phi \rangle^4 m_\phi$$ \hfill (15)

$$\simeq \frac{25g}{8\pi} y^2 \left(\frac{v^2}{g}\right)^{8/5},$$ \hfill (16)

which leads to the reheating temperature given by

$$T_{\text{RH}} \simeq \left(\frac{90}{1000} \Gamma_\phi M_{\text{Pl}}\right)^{1/2}$$ \hfill (17)

$$\simeq 10^9 \text{ GeV} \left(\frac{y}{10}\right) \left(\frac{v}{5 \times 10^{12} \text{ GeV}}\right)^{8/5} \left(\frac{g}{1000}\right)^{-3/10}.$$ \hfill (18)
Figure 1: Contours of reheating temperature in the $v$-$y$ plane. The inflaton cannot decay into $Q$ and $\bar{Q}$ kinematically in the red-shaded region. We set $g = 1000$.

We use the anthropic principle to explain the observed amount of baryon asymmetry. We assume that the baryon asymmetry is generated by the thermal leptogenesis, which requires a reheating temperature larger than of order $10^9$ GeV [21, 41]. We plot the contours of reheating temperature in $v$-$y$ plane with $g = 1000$ in Fig. 1, where the inflaton cannot decay into $Q$ and $\bar{Q}$ kinematically in the red-shaded region. Since lighter gravitino mass is favoured from viewpoint of fine-tunings of electroweak scale and cosmological constant, smaller $v$ should be selected. Thus we find that $T_{RH} \gtrsim 10^9$ GeV and $m_\phi \geq 2m_Q$ imply

$$v \simeq 5 \times 10^{12} \text{ GeV} \quad \quad (19)$$

$$y \simeq 10. \quad \quad (20)$$

It is also consistent with the large value of $g$. From Eqs. (7) and (9), the amplitude of curvature perturbations is predicted to be of order the observed value and the gravitino mass of order 100 TeV.

Here we comment on resonant leptogenesis [42, 43]. If the Yukawa coupling constants for interactions between the right-handed neutrinos and a $B-L$ breaking field can be fine-tuned, the right-handed neutrino mass can be degenerated. In this case, the CP violating effect on their decay can be enhanced by a resonance effect and the lower bound on reheating temperature can be smaller than $10^9$ GeV to explain the observed amount of baryon asymmetry. Here, we provide a conjecture that the Yukawa coupling constants are fixed by a mechanism beyond the present scope of the string landscape. This is motivated by the following discussion. In the SM sector, if the Yukawa coupling constants are not fixed, the Higgs VEV may not be determined by the anthropic principle. In fact, the Higgs VEV of
order 10 TeV may not be excluded [44]. However, it has been argued that the Higgs VEV cannot be larger than about 1 TeV when the Yukawa couplings are fixed [45].

2.3 LSP abundance

We consider wino or higgsino LSP with a mass lighter than $O(1)$ TeV because otherwise its thermal relic abundance is larger than the observed DM abundance [35, 36, 37]. Such a light wino or higgsino in addition to 100 TeV gravitino are naturally realized in pure gravity mediation [38, 39]. In this model, the neutral wino acquires one-loop suppressed soft masses through the anomaly mediated SUSY breaking effect [46, 47]:

$$m_{\tilde{w}} \simeq \frac{g_2^2}{16\pi^2} (m_{3/2} + L)$$  \hspace{1cm} (21)
$$L \equiv \mu_H \sin 2\beta \frac{m_A^2}{|\mu_H|^2 - m_A^2} \log \frac{|\mu_H|^2}{m_A^2},$$  \hspace{1cm} (23)

where $L$ is Higgsino threshold corrections [47, 48], $m_A$ is the mass of the heavy Higgs bosons, $\mu_H$ is the Higgs $\mu$-term, and $\tan \beta$ is the ratio of the VEV of $H_u$ and $H_d$. Neutral higgsino can also be the LSP when $\mu_H$ is smaller than $m_{\tilde{w}}$. The thermal relic abundance of the LSP is subdominant compared with the observed DM abundance when the LSP is wino with mass lighter than 2.9 TeV or higgsino with mass lighter than 1 TeV.

Since the gravitino mass is of order 100 TeV, it decays into radiation before the BBN epoch. The produced LSP from gravitino decay does not overclose the Universe for reheating temperature of order $10^9$ GeV [35].

Indirect detection experiments of DM puts lower bounds on the LSP abundance. If the LSP abundance is equal to that of DM, the wino LSP with $m_{\tilde{w}} \leq 390$ GeV and 2.14 TeV $\leq m_{\tilde{w}} \leq 2.53$ TeV is excluded [49] and the higgsino LSP with $m_{\tilde{h}} \leq 160$ GeV is excluded [50]. The future indirect detection experiments can detect the wino LSP with $m_{\tilde{w}} \leq 1.0$ TeV and 1.66 TeV $\leq m_{\tilde{w}} \leq 2.77$ TeV [49] if it is the dominant component of DM. However, let us emphasize that the LSP may be subdominant component of DM in the anthropic landscape. This is because, as we explain in the next section, the saxion initial amplitude is fine-tuned in the anthropic landscape such that the LSP produced from its decay does not overclose the Universe. Note also that the axion is another candidate of DM and its misalignment angle is fine-tuned such that its energy density is below that of DM.
2.4 Discussion on a small parameter in Kähler potential

In this subsection, we provide a scenario that explains the smallness of the parameter $k$ in the Kähler potential. Suppose that inflation occurs at the GUT scale before the new inflation occurs [17]. Let us emphasize that the observable universe is determined by the new inflation, which lasts more than $50\ e$-foldings, so that there is neither the monopole overproduction problem nor the cosmic string constraint. For example, the GUT-scale inflation can be realized in the following model:

$$W_{\text{GUT}} = \kappa S \left( \psi \bar{\psi} - \mu^2 \right).$$  \hspace{1cm} (24)

where $\kappa$ is a parameter and $\mu = E_{\text{GUT}} \approx 10^{-2}$. When $S$ has a VEV larger than the parameter $\mu$, the hybrid inflation occurs [15, 16].

The Hubble parameter during the GUT-scale inflation is given by

$$H_{\text{GUT}} \simeq \frac{\kappa \mu^2}{\sqrt{3}}.$$ \hspace{1cm} (25)

Through the supergravity effect, the inflaton in the new inflation sector obtains terms of

$$V_H(\phi) = c_H H_{\text{GUT}}^2 |\phi|^2 - a_H \langle W_{\text{GUT}} \rangle v^2 \phi + c.c. + \ldots,$$ \hspace{1cm} (26)

where $\ldots$ represents irrelevant higher-dimensional terms [51]. The Hubble-induced mass term makes $\phi$ stay at the minimum of

$$\langle \phi \rangle_{\text{ini}} \simeq \frac{a_H}{c_H} W_{\text{GUT}} \frac{v^2}{H_{\text{GUT}}^2}$$ \hspace{1cm} (27)

$$\simeq 3 \frac{a_H v^2}{c_H \kappa \mu},$$ \hspace{1cm} (28)

at the end of the GUT-scale inflation. This is also true after the GUT-scale inflation.$^5$

Some time after the GUT-scale inflation ends, the energy density of the Universe becomes dominated by the F-term of $\phi$ and new inflation occurs. Equation (28) gives the initial amplitude of $\phi$ at the beginning of new inflation.

Here let us consider the condition that the new inflation can be eternal inflation [52, 53, 54]. The inflation is eternal when the amplitude of quantum fluctuations of the horizon scale

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$^4$ We assume no mixing between $\phi$ and $S$ in Kähler potential.

$^5$ Note that $W_{\text{GUT}} \simeq \sqrt{2} \kappa \mu S \delta_\psi$ around the minimum of the potential, where the waterfall field $\delta_\psi$ is defined by $\psi = \bar{\psi} = \mu + \delta_\psi / \sqrt{2}$. Since the waterfall field as well as the inflaton $S$ start to oscillate after inflation, $W_{\text{GUT}}$ is in general nonzero and is proportional to $a^{-3} \propto H^2(t)$. Thus, even after the GUT-scale inflation, $\langle \phi \rangle_{\text{ini}}$ is given by Eq. (28) with $O(1)$ suppression due to a phase difference between $S$ and $\delta_\psi$ oscillations.
is larger than the classical motion of $\phi$. This condition is quantitatively written as

$$\frac{H_{new}^2}{\dot{\phi}} > 5,$$

(29)

at the beginning of new inflation. Using the slow roll relation of $\dot{\phi} \approx V_{new}'/3H_{new}$, we can rewrite the condition as

$$5 < \frac{3H_{new}^3}{V_{new}'}$$

(30)

$$\leftrightarrow \langle \phi \rangle_{ini} < \frac{v^2}{5\sqrt{3}k}.$$  

(31)

Together with Eq. (28), this condition can be rewritten as

$$k < \frac{cH}{15\sqrt{3}aH} \mu = O(1) \times \mu$$

(32)

$$\approx 0.01,$$

(33)

where we use $\mu \approx 10^{-2}$ in the last line. Thus the eternal inflation occurs for $k$ of order 0.01. When the eternal inflation occurs, the number of universes becomes infinitely large. On the other hand, the parameter $k$ should be as large as possible. Thus we expect that the parameter $k$ is determined as the largest value with which the new inflation is eternal. This is the reason why the parameter $k$ has a value of order 0.01. As a result, the spectral index is naturally consistent with the observation [see Eq. (6)].

### 3 SUSY axion cosmology

The string theory predicts many axions with their decay constants of order the GUT scale [25, 26, 27]. We expect that at least one of these axions couples to gluons so that the strong CP problem is solved by the Peccei-Quinn (PQ) mechanism [22]. This is very interesting because the smallness of the strong CP phase cannot be explained in the anthropic landscape. In fact, we can live in a universe with the strong CP phase $\theta \sim 10^{-2}$, which is much larger value than the experimental constraint $\theta < 10^{-10}$ [55]. Although an axion oscillation with a string-scale decay constant may overclose the Universe after the QCD phase transition [56, 57, 58], this problem can be addressed by the fine-tuning of its initial angle in the anthropic landscape. This implies that the axion contributes to DM with a fraction of order unity.

In SUSY, there is a super-partner of axion, called saxion, so that we have to take into account its dynamics in the early Universe. The saxion has a mass of order the gravitino mass and it starts to oscillate around its low-energy minimum when the Hubble parameter
decreases to its mass scale. Since the initial amplitude of saxion oscillation is naively of order the GUT scale, its energy density may soon overclose the Universe. This problem can be addressed by the fine-tuning of its initial amplitude in the anthropic landscape. This scenario is similar to the one in our previous work [59], where we assumed that the R-parity and matter parity are violated so that the LSP produced from saxion decay also decays before the BBN epoch in order not to overclose the Universe. However, the matter parity may be originated from the spontaneous breaking of $U(1)_{B-L}$ symmetry, which naturally results in the realization of seesaw mechanism to account for the smallness of left-handed neutrino masses [60].

Motivated by this issue, in this paper we consider the case that the R-parity and matter parity is conserved and the LSP is stable. In this case, the saxion initial VEV is fine-tuned in the anthropic landscape so that the LSP produced from saxion decay does not overclose the Universe. This implies that the saxion decay does not produce much entropy and hence the baryon number produced via the thermal leptogenesis is not diluted.

### 3.1 Saxion decay

As we discuss in the previous section, the anthropic landscape implies the gravitino mass of order 100 TeV. Thus the mass of saxion is also of order 100 TeV. Here we consider saxion decay and check that it decays before the BBN epoch not to spoil the success of the BBN theory [34].

The saxion decays into gauge bosons and gauginos through

$$\mathcal{L} \supset \int d^2 \theta \sqrt{2} g^2 A \frac{1}{32 \pi^2 f_a} W^\alpha W_\alpha + h.c.,$$  

(34)

where $A$ is an axion chiral superfield and $f_a$ is the axion decay constant of order the GUT scale. The decay rate of saxion into gluons is given by

$$\Gamma_g = \frac{\alpha_s^2 m_\sigma^3}{32 \pi^3 f_a^4},$$  

(35)

where $m_\sigma$ is saxion mass. If kinematically allowed, the saxion decays also into gluinos with a rate of $\Gamma_{\tilde{g}} \simeq (m_{3/2}/m_\sigma)^2 \Gamma_g$. Its decay temperature is therefore given by

$$T_d \simeq 11 \text{ MeV} \left( \frac{m_\sigma}{100 \text{ TeV}} \right)^{3/2} \left( \frac{f_a}{10^{16} \text{ GeV}} \right)^{-1}. $$  

(36)

This should be larger than 1 MeV not to spoil the success of the BBN theory [34]. The saxion mass of order 100 TeV is consistent with this bound.

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6 Although the R-parity can be originated from $Z_{10R}$ defined in Table. 1, it is not the case in general.

7 One might wonder that the mass of LSP can be fine-tuned instead of the fine-tuning of saxion initial VEV so that its abundance does not overclose the Universe. However, the fine-tuning of the LSP mass is severer than that of the saxion initial VEV. Thus the latter scenario is favoured in the anthropic landscape.
### 3.2 Axion isocurvature

Next we consider the axion isocurvature perturbation problem. Since the axion is massless, it acquires quantum fluctuations during inflation \[28, 29, 30, 31, 32\]:

\[
\delta a \simeq \frac{H_{\text{new}}}{2\pi}.
\]  

(37)

After inflation, the axion fluctuations lead to isocurvature modes in density perturbations whose amplitude is given by

\[
P_{\text{iso}} \simeq \left(\frac{\Omega_a h^2}{\Omega_{\text{DM}} h^2}\right)^2 \left(\frac{H_{\text{inf}}}{\pi f_a \theta_{\text{ini}}}\right)^2,
\]  

(38)

where \(\theta_{\text{ini}}\) is the axion misalignment angle and \(\Omega_a\) is the axion abundance. This amplitude is bounded above by the observations of CMB fluctuations \[33\]:

\[
\beta_{\text{iso}} \equiv \frac{P_{\text{iso}}}{P_{\text{ad}}} < 0.037,
\]  

(39)

where the amplitude of adiabatic perturbations is measured such as \(P_{\text{ad}} \simeq 2.2 \times 10^{-9}\) \[33\]. In the anthropic landscape, the axion misalignment angle is fine-tuned such that its oscillation energy density does not overclose the Universe. This implies that \(\theta_{\text{ini}} \lesssim 0.003\) for \(f_a \simeq 10^{16}\) GeV \[56, 57, 58\] and its energy density contributes an \(O(1)\) fraction of total DM density in our Universe. Thus the isocurvature constraint implies that the energy scale of inflation is bounded above such as

\[
H_{\text{new}} \lesssim 9.6 \times 10^8 \text{ GeV} \left(\frac{\Omega_a h^2}{0.12}\right)^{-1/2} \left(\frac{f_a}{10^{16}\text{ GeV}}\right)^{0.4}.
\]  

(40)

where we use \(\Omega_{\text{DM}} h^2 \simeq 0.12\). This is satisfied in the new inflation model considered in the previous section.

Note that the axion isocurvature constraint cannot be avoided directly in the anthropic landscape because our Universe can exist with an \(O(1)\) fraction of isocurvature modes. Low-scale inflation is implied by the string landscape and the new inflation model is a natural realization of such low scale inflation.

### 4 Conclusion

We consider a new inflation model where R-symmetry is broken at the minimum of inflaton potential. The reheating temperature is related to the VEV of the inflaton, so that the
gravitino mass, which is proportional to the R-symmetry breaking effect, is then related to the reheating temperature. As a result, the realization of thermal leptogenesis requires gravitino mass heavier than 100 TeV. This is consistent with the present constraint on SUSY breaking scale and the 125 GeV Higgs boson. Furthermore, the new inflation consistently predicts the amplitude of density perturbations. The spectral index can be consistent with the observed value when we allow a fine-tuning in the Kähler potential. This fine-tuning could be explained once we require eternal inflation in the new inflation.

Other cosmological problems are also addressed in this scenario by the heavy gravitino and the anthropic landscape. String axions do not overclose the Universe by the fine-tuning of their initial amplitudes in the anthropic landscape. The axion isocurvature fluctuations are suppressed because the energy scale is sufficiently low in the new inflation model. Saxions are so heavy that they decay into LSP before the BBN epoch because the gravitino mass is of order 100 TeV. We assume R-parity conservation so that the saxion initial amplitude is fine-tuned such that its decay products do not overclose the Universe. This implies that saxions never dominate the Universe and hence the saxion decays do not produce a large entropy, which is crucial for the successful thermal leptogenesis. The string landscape implies that DM is the mixture of axion and LSP (wino or higgsino). This means that the constraint on wino DM by the indirect DM search experiments can be avoided even if the mass of wino is so small that we can find it by the LHC experiment with 13 TeV center of energy.

Acknowledgments

T. T. Y. thanks Prof. Raymond Volkas for the hospitality during his stay at the University of Melbourne. This work is supported by Grants-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan, No. 25400248 (M. K.) and No. 26104009 (T. T. Y.); MEXT Grant-in-Aid for Scientific Research on Innovative Areas No.15H05889 (M. K.); Grant-in-Aid No. 26287039 (T. T. Y.) from the Japan Society for the Promotion of Science (JSPS); World Premier International Research Center Initiative (WPI), MEXT, Japan (M. K., M. Y., and T. T. Y.), and the Program for the Leading Graduate Schools, MEXT, Japan (M.Y.). M.Y. acknowledges the support by the JSPS Research Fellowships for Young Scientists, No. 25.8715. The research leading to these results has received funding from the European Research Council under the European Unions Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. 279972 “NPFlavour” (N.Y.).
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