Electroweak relaxation of cosmological hierarchy

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A simple model for the late-time cosmic acceleration problem is presented in the Starobinsky inflation with a negative bare cosmological constant as well as a non-minimal coupling to Higgs boson. After electroweak symmetry breaking, the Starobinsky inflaton is frozen until very recently becoming a thawing quintessence, and a comparable magnitude to the observed dark energy density can be achieved without fine-tuning. Our proposal essentially reduces the cosmological constant problem into the electroweak hierarchy problem, and its late-time behaviour is also consistent with the recently proposed swampland criteria.

Introduction. — Although physics at different energy scales are decoupled with each other according to the renormalization group (RG) flow, the energy scales themselves could still reveal us some connections among physics at these scales. It has long been noticed that, the energy scale of the currently observed dark energy density $\Lambda_{DE} \sim (10^{-12} \text{ GeV})^4$ could be expressed as

$$\Lambda_{DE}^2 \sim H_0 M_{Pl}, \quad (1)$$

where the Planck scale $M_{Pl} \sim 10^{18} \text{ GeV}$ is the smallest ultraviolet (UV) length scale and the current Hubble scale $H_0 \sim 10^{-42} \text{ GeV}$ is the largest infrared (IR) length scale. This suspicious UV/IR mixing relation has inspired some quests for the late-time cosmic acceleration problem. The same pattern is also realized in the recently proposed swampland criteria.

A simple model for the late-time cosmic acceleration problem is presented in the Starobinsky inflation with a negative bare cosmological constant as well as a non-minimal coupling to Higgs potential. The comparable magnitude to the observed dark energy density can be achieved without fine-tuning. Our proposal essentially reduces the cosmological constant problem into the electroweak hierarchy problem, and its late-time behaviour is also consistent with the recently proposed swampland criteria.

$$\Lambda_{inf}^2 \sim M_{Pl} H_{inf}, \quad (2)$$

that can be recognized trivially as the Friedman equation. The face values $\Lambda_{inf} \sim 10^{16} \text{ GeV}$ and $H_{inf} \sim 10^{14} \text{ GeV}$ could be inferred from the current constraint on the tensor-to-scalar ratio $r \lesssim 0.01$.

A similar relation was observed recently in the late-time cosmic acceleration problem. The model in [7] has serious drawback that, at the quantum level, the non-canonical kinetic term $(h/v)^2(\partial\phi/\phi)^2$ is only suppressed by the EW scale, leaving observable signals that would be otherwise detected in the Higgs decay channels long time ago. Furthermore, the construction in (3) seems highly non-trivial and unnatural.

In this letter, a simple and natural model to reproduce the relation (3) is constructed in the standard Starobinsky inflation model [9] with a negative bare cosmological constant as well as a non-minimal coupling to Higgs boson. After Starobinsky inflation and subsequent reheating, the inflaton remnant stays at a minimal slightly shifted from the origin due to a non-zero Higgs potential value $V(0) = \alpha^2 M_{Pl}^4$ in symmetric phase with $\lambda = 0.129$. Once the EW symmetry is broken, Higgs is relaxed to the EW vacuum and inflaton is frozen by a dubbed bait-and-switch mechanism at a potential energy density

$$c^2 V(h = 0)^2 = \frac{c^2 M_{Pl}^4}{16\alpha^2 M_{Pl}^4} = 4c^2 \times 10^{-48} \text{ GeV}^4 \quad (5)$$

that could match the currently observed dark energy density $\rho_{DE} \sim 2.58 \times 10^{-47} \text{ GeV}^4$ for $c \approx 2.5$ without fine-tuning. After that, the frozen inflaton starts rolling down a quintessential potential when the Hubble parameter drops down to its current value. Unfortunately, the model in (5) has serious drawback that, at the quantum level, the non-canonical kinetic term $(h/v)^2(\partial\phi/\phi)^2$ is only suppressed by the EW scale, leaving observable signals that would be otherwise detected in the Higgs decay channels long time ago. Furthermore, the construction in (3) seems highly non-trivial and unnatural.

In this letter, a simple and natural model to reproduce the relation (3) is constructed in the standard Starobinsky inflation model with a negative bare cosmological constant as well as a non-minimal coupling to Higgs boson. The general picture of (7) is retained without the use of any non-canonical kinetic term and non-standard Higgs potential. The comparable magnitude to the observed dark energy density can be achieved without fine-tuning thanks to the relation (3). Our proposal is also consistent with the recently proposed swampland criteria due to the transformed role of inflaton as a thawing quintessence at late-time.
The model. — The action of our proposal in Jordan frame is
\[ S_J = \int d^4x \sqrt{-g} \left[ \frac{M^2}{2} \left( 1 + \frac{R}{8\alpha_2 M^2} + \frac{\xi h^2}{M^2} \right) R - \frac{s^2}{16\alpha_2^2} \right] - \frac{1}{2} \left( \partial h \right)^2 - V(h) - \mathcal{L}_{\text{SM+DM}}, \tag{6} \]
where \( M \) is a unknown energy scale for \( R^2 \) gravity to be fixed later, \( \alpha \) is a inflationary parameter to be fixed by observation, \( \xi \) is a non-minimal coupling of Higgs field to Ricci scalar \( R \) that eventually will be generated at loop-order even if it is absent at tree-level \[13\], \( \Lambda_b \) is a bare cosmological constant that turns out to be negative later, \( V(h) \) is the usual Higgs potential of form
\[ V(h) = \left\{ \begin{array}{ll}
\frac{1}{2} h^4 + \frac{1}{4} v^4, & \text{symmetric phase;}
\frac{1}{2} (h^2 - v^2)^2, & \text{broken phase,}
\end{array} \right. \tag{7} \]
with \( \lambda = 0.13 \). The Lagrangian \( \mathcal{L}_{\text{SM+DM}} \) for the SM along with an unknown dark matter (DM) sector will be left implicitly thereafter. See e.g. \[14-16\] for similar actions. For the sake of simplicity, we will get rid of the tilde symbol and use following short notations
\[ \omega^2 \equiv \frac{1}{2} h^2 - v^2, \quad \omega_0^2 = \frac{1}{2} \xi v^2, \quad \omega_b^2 = 1; \tag{14} \]
\[ S = \frac{s}{4\alpha_2 M^2}, \quad S_0 = \frac{s_0}{4\alpha_2 M^2}, \quad \Omega_h^2(S) = S - S_0 + \omega_b^2; \tag{15} \]
\[ U_h = \frac{\Lambda^4 + V(h)}{\alpha^2 M_P^4}, \quad U_0 = \frac{\Lambda^4}{\alpha^2 M_P^4} + \frac{V(0)}{\alpha^2 M_P^4} = U_0 + V_0, \tag{16} \]
to express the action in Einstein frame as
\[ S_E = \int d^4x \sqrt{-g} \left[ \frac{M_P^2}{2} R - \frac{1}{2} \left( \partial \psi_h \right)^2 - \frac{1}{2} \Omega^2 \right] + \frac{1}{2} \left( \partial h \right)^2 - \frac{s^2}{16\alpha_2^2} - \Lambda_b^4 - V(h) \right], \tag{17} \]
where the potential term in the second line will be denoted as \( W(S, h) \).

Starobinsky inflation. — To have a successful Starobinsky inflation before EW symmetry breaking, \( \omega_0^2 - S_0 \) in \[13\] should be positive, thus \( \omega_b^2 - S_0 = \exp \left( \sqrt{\frac{2}{\xi} c} \right) \) for some constant \( c \). Furthermore, the bare cosmological constant term in \[17\] should not interfere the end of inflation roughly at \( \phi_{\text{end}} / M_P = 1 + c \), namely
\[ (\Lambda^4 + V(0)) e^{-2\sqrt{2}(1+c)} \ll \alpha^2 M_P^4 \left( 1 - e^{-\sqrt{2}} \right)^2, \tag{18} \]
leading to a constraint
\[ \frac{U_0}{(\omega_0^2 - S_0)^2} \ll \left( e^{\sqrt{2}} - 1 \right)^2 \approx 1.6, \tag{19} \]
that will be checked later. Another constraint comes from the suppression of fluctuations in the Higgs sector to preserve the inflationary prediction of Starobinsky inflation. This requires the effective mass of the kinetically normalized Higgs \( \chi \) from \( (d\chi/d\phi)^2 = \Omega_h^2 \) to be larger than the inflationary Hubble scale,
\[ m_\chi^2 = \Omega_h^2 W''(S, 0) = \frac{4\xi}{M_P^4} \left( \alpha^2 M_P^4 \frac{S^2}{\Omega_h^2(S)} + \frac{\Lambda^4 + V(0)}{\Omega_h^2(S)} \right); \]
\[ \approx \frac{4\xi S^2}{3\Omega_h^2(S)} \alpha^2 M_P^4 \gg H^2 = \frac{S^2}{3\Omega_h^2(S)} \alpha^2 M_P^4, \tag{20} \]
namely $|\xi| \gg 1/12$, which will also be checked later. For now, we will assume that these two constraints are satisfied so that Starobinsky inflation could proceed as usual.

After Starobinsky inflation and subsequent reheating, the inflaton remnant, if not decays away totally, stays at a local minimum $(S_{EW}, h = 0)$ determined from the condition

$$W_{\phi}'(S_{EW}, 0) = \sqrt{\frac{8}{3} \frac{1}{M_{Pl}^2} \frac{S_{EW}(\omega^2 - S_0) - U_0}{\Omega^2_{2}(S_{EW})}} = 0,$$  \hspace{1cm} (21)

which gives rise to the field value of Starobinsky scalaron just before EW symmetry breaking,

$$S_{EW} = \frac{U_0}{\omega^2 - S_0}. \hspace{1cm} (22)$$

**EW symmetry breaking.** — When EW symmetry is broken, Higgs is relaxed to its current minimum $h = v$ and the potential energy density is of form

$$W(S_{EW}, v) = \alpha^2 M_{Pl}^4 \frac{U_v + S^2_{EW}}{(1 - S_0 + S_{EW})^2}. \hspace{1cm} (23)$$

To retain the success of picture observed in [7], $\varphi$ should be frozen right after EW symmetry breaking by requiring a light effective mass of $\varphi$,

$$m_{\varphi}^2 = W_{\varphi\varphi}(S_{EW}, v); \hspace{1cm} (24)$$

If the observation from relation [3] indeed reveals the myth of dark energy, all we have to do is to solve the fixing condition [23] and freezing condition [24], namely,

$$aV^2_0 = \frac{U_v + S^2_{EW}}{(1 - S_0 + S_{EW})^2}; \hspace{1cm} (25)$$

$$bV^2_0 = \frac{2U_v + (1 - S_0)(1 - S_0 - S_{EW})}{(1 - S_0 + S_{EW})^2}. \hspace{1cm} (26)$$

To match the currently observed dark energy density $W(S_{EW}, v) \sim \Lambda^4_{DE}$ and thawing behaviour $m_{\varphi}^2 \sim H^2_0$, one only needs for the order-of-one parameters $a = 25/4$ and $b = a/4\Omega$ with $\Omega_A \approx 0.7$ today.

Solving [25] and [26] is a non-trivial task. The only freedom comes from the normalized scalaron value $S_0$ where Einstein gravity is fixed. By choosing $S_0$ away from 1, one expects following approximated solutions

$$\omega^2_0 = \frac{3}{2}S_0 - \frac{1}{2}; \hspace{1cm} (27)$$

$$U_v \approx -\frac{1}{4}(S_0 - 1)^2. \hspace{1cm} (28)$$

However, these solutions does not allow for the desirable behaviour at both early-time and late-time that necessarily requiring $\omega^2_0 - S_0 > 0$ and $1 - S_0 > 0$ from [13].

**Thawing quintessence.** — It turns out as a nice surprise that, when $S_0$ is close to 1, the position of $S_0$ with desirable solutions is independent from the parameters $a$ and $b$. To see this, one could take a concrete example by choosing $S_0 = 1 - V_0$ without lost of generality. The equations [25] and [26] are solved to give

$$\omega^2_0 = 3 - \frac{3}{2}V_0 + (3b - 6a)V^2_0 + O(V^3_0); \hspace{1cm} (29)$$

$$U_v = -\frac{1}{4}V^2_0 + \frac{3}{4}(a + b)V^3_0 + O(V^4_0). \hspace{1cm} (30)$$

that truncated at the order when parameters $a$ and $b$ is first appear. The leading order terms of [29] and [30] is indeed independent from the choice of how close $S_0$ is to 1.

The potentials in [13] along $\psi_3$ direction in the symmetric and broken phase are presented in Fig. 11 with above truncated solutions from $S_0 = 1 - V_0$, where the EW symmetry breaking occurs in the normalized scalaron value $S_{EW} = V_0/2 + (6a - 3b)V^3_0/4 + \mathcal{O}(V^4_0)$ with $\Omega^2_0(S_{EW}) = 2 + (36a - 6b)V^2_0 + \mathcal{O}(V^4_0)$ and $\Omega^2_0(S_{EW}) = 3V_0/2 + (6a - 3b)V^3_0/4 + \mathcal{O}(V^4_0)$, namely $\varphi_{EW} = \sqrt{3/2}\ln\Omega^2_0(S_{EW}) = 0.8489M_{Pl}$ and $\varphi_{EW} = \sqrt{3/2}\ln\Omega^2_0(S_{EW}) = -151.788M_{Pl}$. The broken-phase potential is thus shifted appropriately for clarity. The normalized scalaron value at final AdS minimum in the broken phase is $S_{min} = -V_0/4 + 3(a + b)V^3_0/4 + \mathcal{O}(V^4_0)$ with $\Omega^2_0(S_{min}) = 3V_0/4 + 3(a + b)V^3_0/4 + \mathcal{O}(V^4_0)$, namely $\varphi_{min} = \sqrt{3/2}\ln\Omega^2_0(S_{min}) = -152.637M_{Pl}$. Note that the rolling of $\varphi$ in the future $\Delta\varphi = \varphi_{EW} - \varphi_{min} = \varphi_{EW}$ is a sub-Planckian field excursion.

Using the truncated solutions [29] and [30], one can check that the original equations [25] and [26] are trivially satisfied at the leading order,

$$\frac{U_v + S^2_{EW}}{(1 - S_0 + S_{EW})^2} = aV^2_0 + \frac{4a + b}{12}V^3_0 + \mathcal{O}(V^4_0); \hspace{1cm} (31)$$

$$\frac{2U_v + (1 - S_0)(1 - S_0 - S_{EW})}{(1 - S_0 + S_{EW})^2} = bV^2_0 - \frac{4a + b}{12}V^3_0 + \mathcal{O}(V^4_0), \hspace{1cm} (32)$$

which freezes the inflaton at the right position after EW symmetry breaking with a potential energy density and effective mass

$$W(S_{EW}, v) = a \frac{V(0)^2}{\alpha^2 M_{Pl}^2} \approx \Lambda^4_{DE}; \hspace{1cm} (33)$$

$$m_{\varphi}^2(S_{EW}, v) = \frac{4b}{3M_{Pl}^2} \frac{V(0)^2}{\alpha^2 M_{Pl}^2} \approx H^2_0, \hspace{1cm} (34)$$

desirable for our purpose. The Starobinsky inflaton is thus frozen until Hubble parameter drops down to its current value and becoming a thawing quintessence today, which also explains the coincidence problem.

One can also check the early-time behaviour from the truncated solutions [29] and [30]. During inflation, the
constraint \([19]\) is explicitly satisfied,
\[
\frac{U_0}{(\omega_0^2 - S_0)^2} = \frac{1}{4} V_0 + \frac{1}{16} V_0^2 + O(V_0^3) \ll 1.6. \tag{35}
\]
The other constraint \([20]\), or equivalently \(|\xi| \gg 1/12\), is also explicitly satisfied from \([29]\), namely
\[
-\xi = \frac{M_{Pl}^2}{v^2} \left( 2 - \frac{3}{2} V_0 + O(V_0^2) \right) \approx 10^{32} \gg 1/12. \tag{36}
\]

Note that the constraint \([18]\) on \(|\xi| \lesssim 10^{15}\) is not applicable here due to the presence of \(R^2\) gravity in addition to the non-minimal coupling. The decay channel of Higgs to quintessence from coupling term \(\exp(-\sqrt{2} \varphi/M_{Pl})/\partial h)^2\) is highly suppressed by the Planck scale, leaving no trace in the collider. The Planckian suppressed effect on various couplings in SM potential also evades the bounds from fifth force. The large effective mass of Higgs during inflation could protect it from the dangerous quantum kick into the unwanted large-field minimum. The Higgs instability problem (See e.g. \([19, 20]\) for a brief review) is thus cured as a by-product.

**swampland criteria.** — The standard single-field slow-roll inflationary paradigm currently faces some tension \([21]\) with the original de Sitter conjecture in swampland criteria \([10, 11]\) as well as the refined de Sitter conjecture \([12]\) (see also \([22]\)) that either one of the following conditions
\[
|\nabla V| \geq \frac{c}{M_{Pl}} V; \quad \min(\nabla_i \nabla_j V) \leq -\frac{c'}{M_{Pl}^2} V; \tag{37, 38}
\]
is fulfilled for some universal constants \(c, c' > 0\) of order 1. Here \(V\) is a potential of scalar fields \(\phi_i\) in a low energy effective theory of any consistent quantum gravity, and the minimum eigenvalue in the second condition is taken for the Hessian operator \(\nabla_i \nabla_j V\) in an orthonormal frame. See also \([22, 29]\) for possible ways out of swampland and \([30, 18]\) for the implications and \([49, 58]\) for the debates.

Although our action \([4]\) contains a bare cosmological constant, which turns out to be mildly negative deduced from \([30]\),
\[
\Lambda_0^4 \approx -\frac{1}{4} \frac{V(0)^2}{\alpha^2 M_{Pl}^4} \sim -\Lambda_{DE}^4, \tag{39}
\]
the plateau potential is currently in tension with the swampland criteria, unless turning to, for example, warm inflation \([27, 29]\) or non-Bunch-Davies initial states \([24, 28]\). Nevertheless, the late-time behaviour of our proposal is consistent with the original de Sitter conjecture in swampland criteria due the transformed role of Starobinsky inflaton as thawing quintessence with
\[
M_{Pl} \frac{\nabla_\varphi W(S_{EW}, v)}{W(S_{EW}, v)} = \sqrt{8} \frac{(1 - S_0) S_{EW} - U_v}{S_{EW}^2 + U_v} \approx \frac{2}{3a} \sqrt{\frac{2}{3}} V_0^{-2} \gg O(1), \tag{40}
\]
while
\[
M_{Pl}^2 \min(\nabla_i \nabla_j W) = \frac{M_{Pl}^2}{3} \frac{\nabla_\varphi \nabla_\varphi W}{W(S_{EW}, v)} \approx \frac{4}{3} \frac{(1 - S_0)(1 - S_0 - S_{EW}) + 2U_v}{S_{EW}^2 + U_v} \approx \frac{4b}{3a} = \frac{1}{3 \Omega_\Lambda}. \tag{41}
\]

The future destiny of our Universe is starting rolling down the quintessential potential and eventually crossing the zero point of potential and inevitably approaching the final AdS minimum with potential energy density
\[
W(S_{\min}, v) = \alpha^2 M_{Pl}^4 \left( \frac{U_v + \left( \frac{U_v}{1 - S_0} \right)^2}{(1 - S_0 + \frac{U_v}{1 - S_0})^2} \right) \approx -\frac{1}{3} \alpha^2 M_{Pl}^4 \tag{42}
\]
within one Planckian field excursion, \(\Delta \varphi = \varphi_{EW} - \varphi_{\min} = \phi_{EW} \approx 0.85 M_{Pl}\), which is also consistent with the distance conjecture of swampland criteria \([10, 11]\).

**Conclusion.** — To naturally reproduce the conspired relation among the interplay of EW scale and inflationary scale with dark energy scale, we propose a simple model of quintessential Starobinsky inflation to address the late-time cosmic acceleration problem. The model in Jordan frame is simply defined in \(R^2\) gravity with a bare negative cosmological constant term as well as a non-minimal coupling of Higgs to Ricci scalar. When transformed into Einstein frame, the Starobinsky inflation is obtained, and the Higgs instability problem is solved due
to a large effective mass. After EW symmetry breaking, the Starobinsky inflaton is frozen at a potential energy density comparable to the currently observed dark energy density without fine-tuning. Only until recently when the Hubble parameter drops down to its current value, the inflaton starts rolling down a quintessential potential and eventually ended up in a AdS state within one Plankian field excursion. The late-time behaviour is consistent with the recent proposed swampland criteria.

Discussion. — There are infinite truncated solutions to the equations (25) and (26) with similar leading order terms on the right-hand-side when $S_0$ is close to 1−, which might be regarded as a reflection of the string landscape at EFT level. Any solution with $S_0$ chosen to be away from 1 is in the regime of string swampland, where our observable Universes cannot be obtained. Even in the regime of string landscape, larger value of EW scale than the currently measured value would either freeze the inflaton at large energy density so that life cannot have enough time to form, or be incapable of freezing the inflaton at all so that our Universe quickly rolls down to the final AdS minimum. Therefore, anthropic principle for EW hierarchy problem is thus implied. With this respect, although the cosmological constant problem can be naturally solved in light of relation (3) within our model, an explanation for a relatively small EW scale is still needed, for example, supersymmetry [59], extra dimensions [60, 61], strong dynamics [62, 63], cosmological relaxation [64] and Naturalness [65].

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