Modulus stabilization of generalized Randall Sundrum model with bulk scalar field

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Abstract

We study the stabilization of inter-brane spacing modulus of generalized warped brane models with a nonzero brane cosmological constant. Employing Goldberger-Wise stabilization prescription of brane world models with a bulk scalar field, we show that the stabilized value of the modulus generally depends on the value of the brane cosmological constant. Our result further reveals that the stabilized modulus value corresponding to a vanishingly small cosmological constant can only resolve the gauge hierarchy problem simultaneously. This in turn vindicates the original Randall-Sundrum model where the 3-brane cosmological constant was chosen to be zero.

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I. INTRODUCTION

A novel solution to the gauge hierarchy problem in the standard model of elementary particles was proposed by Randall and Sundrum [1] through an exponential warping of the space-time metric in a five dimensional anti-de Sitter space-time compactified on a $S^1/Z_2$ orbifold. The five dimensional metric has a solution:

$$ds^2 = e^{-kr_c|\phi|}g_{\mu\nu}dx^\mu dx^\nu + r_c^2d\phi^2 \quad (1.1)$$

where $k$ is of the order of Planck scale ($M_{Pl}$) and $r_c$ specifies the radius of the extra dimension. Two 3-branes are located at the orbifold fixed points $\phi = \pi$ (visible) and $\phi = 0$ (hidden). Due to warping of 4D space-time metric all the fundamental scalar masses get rescaled on the visible brane and a fundamental mass ($m_0$) of Planck scale order comes down to a physical mass scale ($m$) of order TeV on the visible brane through the relation: $m = m_0e^{-kr_c\pi}$. In the RS model the radius of extra dimension is suitably fine tuned as $kr_c \approx 12$ so that the gauge hierarchy problem can be resolved without introducing any intermediate mass scale in the theory. This can be achieved by choosing $k$ (which is related to the bulk cosmological constant) and the inverse of $r_c$ of the order of Planck mass. However without any dynamical basis for this fine tuning, it became imperative to introduce dynamics which determines a stabilized location of the TeV brane relative to the Planck brane.

It was proposed by Goldberger and Wise (GW) [4] that the dynamics of a five dimensional bulk scalar field in such models could stabilize the size of the extra dimension to it’s desired value. In this mechanism the effective potential for the modulus has been generated by the total action integral of a bulk scalar field with quartic interactions localized in two 3-branes. The bulk scalar then acts like a spring between the branes, whose gradient energy becomes repulsive if the branes get too close, and whose potential energy (from $m^2\phi^2$) causes attraction if the branes separate too much. In this way the minimum of the modulus (brane separation) potential yields a compactification scale in terms of the ratio of VEV’s of the scalar fields at the two branes which solves the gauge hierarchy problem without fine tuning any of the parameter of the theory. Initially GW neglected the back reaction of the bulk scalar on the geometry as well as on the brane tensions. Later the back reaction has been included in [5] and some critical studies have been done in [6]. Several variations of the GW mechanism in higher dimensions [7], in cosmological braneworlds [8] and with non minimal
scalar fields have been studied rigorously. This stabilization mechanism has also been generalized for supersymmetric warped space-times.

In the present work we will apply the GW mechanism of radius stabilization in the braneworld model with nonzero brane cosmological constant. As can be seen that the original Randall-Sundrum model started with flat 3-branes, it has been shown in [2] that one can indeed generalize the model with non-zero cosmological constant on the brane and still can have Planck to TeV scale warping from the resulting warp factor. Different values of the inter-brane separation modulus for different values for the brane cosmological constant (Ω) are obtained through their functional relation such that the gauge hierarchy problem is resolved for this entire region of the parameter space. The analysis has been done for both de-Sitter and anti-de Sitter TeV branes by choosing appropriate signature for Ω and the corresponding brane tensions have been determined. Motivations for this analysis as well as that presented in this work have their roots in the observational support in favour of de-Sitter-like character of our universe. The present accelerating phase of our universe can be explained by the presence of a small but positive cosmological constant whose value is estimated to be \( \sim 10^{-124} \) in Planck unit. Despite such a tiny value it is responsible in inducting such a large acceleration to the expansion of the universe. It is therefore worthwhile to to explore the effects of a non-vanishing cosmological constant on the brane particularly in the context of gauge hierarchy and modulus stabilization.

In this work we study the stabilization of such a generalized RS model in the light of Goldberger-Wise mechanism by introducing a scalar field in the bulk. We show that such a stabilization is indeed possible and the stable value of the modulus depends on the value of the brane cosmological constant. However for a given value of the cosmological constant the corresponding stable value of the modulus will resolve the gauge hierarchy problem also only when the value of the cosmological constant is vanishingly small. In other words the modulus-cosmological constant relation to resolve the gauge hierarchy problem and the modulus -cosmological relation to achieve stability will have common solution only in the region of vanishingly small cosmological constant. We shall discuss these issues more quantitatively in the context of the presently observed value of the cosmological constant at the end of our analysis.

In this paper we first briefly summarize the braneworld model with non zero brane cosmological constants as found in [2]. The detailed analysis of the stability mechanism has
been presented in the next section. Finally we conclude with the summary of our results and discuss some open issues.

II. MODEL

In the Randall and Sundrum [1] warped braneworld model the cosmological constant induced on the visible brane is zero which is not consistent with the present day observed small positive value of the cosmological constant. Moreover the consistent boundary condition requires that the tension of the visible TeV brane must be negative which in turn indicates an intrinsic instability. In an attempt to generalize this model it has been demonstrated in [2] that the condition of zero cosmological constant on the brane may be relaxed for a more general warp factor which includes branes with non-zero cosmological constant. Another important aspect of the model [2] is that in some circumstances the visible brane tension may become positive also. Let us now discuss the model briefly. In this model the warped geometry has been obtained by considering a constant curvature brane space-time. General form of the warped metric for a five dimensional space-time is given by,

$$ds^2 = e^{-2A(y)} g_{\mu\nu} dx^\mu dx^\nu + dy^2$$

where $g_{\mu\nu}$ stands for four dimensional curved brane. There are two branes located at orbifold fixed points $y = 0$ and $y = r\pi$ where $r$ corresponds to the modulus associated with the extra dimension. The bulk consists of a negative cosmological constant, $\Lambda$. A scalar mass on the visible brane gets warped through the warp factor $e^{-A(kr\pi)} = \frac{m}{m_0} = 10^{-n}$ where, $k = \sqrt{-\frac{\Lambda}{12M^2}} \sim$ Planck Mass and ‘$n$’, the warp factor index is set to 16 to achieve the desired warping from Planck to TeV scale. The magnitude of the induced cosmological constant on the brane in this case is non-vanishing in general and is given by $= 10^{-N}$ (in Planck units). For a negative brane cosmological constant, $N$ has minimum value given by $N_{\text{min}} = 2n$ leading to an upper bound on the magnitude of the cosmological constant (depending on the choice of the warp factor index $n$). There is no such upper bound for the induced positive cosmological constant on the brane. For brane cosmological constant, $\Omega > 0$ and $\Omega < 0$, the brane metric $g_{\mu\nu}$ may correspond to different space-time geometry such as dS-Schwarzschild and AdS-Schwarzschild spacetimes respectively.
A. AdS Brane:

For the negative value of the cosmological constant $\Omega$ on the visible brane if one redefines $\omega^2 \equiv -\Omega/3k^2 \geq 0$ then the solution of the warp factor can be written as:

$$e^{-A} = \omega \cosh \left( \ln \frac{\omega}{c_1} + ky \right)$$  \hspace{1cm} (2.2)

where $c_1 = 1 + \sqrt{1 - \omega^2}$ for which the warp factor is normalized to unity at $y = 0$. One can show that real solution for the warp factor exists if and only if $\omega^2 \leq 10^{-2n}$. This leads to an upper bound for the magnitude of the cosmological constant as $N_{\text{min}} = 2n$. So, for $n = 16$ , $N$ is found to be $10^{-32}$. For $N = N_{\text{min}}$, one obtains a degenerate solution $kr\pi = n \ln 10 + \ln 2$. For $N - 2n >> 1$, the solutions obtained in this case, are

$$kr_1\pi = n \ln 10 + \frac{1}{4} 10^{-(N-2n)}$$
$$kr_2\pi = (N-n) \ln 10 + \ln 4$$ \hspace{1cm} (2.3)

As an example, to have a solution of the gauge hierarchy problem with the small non zero value of the brane cosmological constant we consider $n = 16$ and $N = 124$ for which the values in the above equation become

$$k\pi r_1 \approx 36.84 + 10^{-93}$$
$$k\pi r_2 = 250.07$$ \hspace{1cm} (2.4)

Note that for $x = n \ln 10$ and $N = \infty$, the RS value can be recovered. At $kr\pi = n \ln 10 + \ln 2$ and $N = 2n$, $\omega^2$ reaches to its maximum value. Beyond this the magnitude of $\omega^2$ starts to decrease again. One can also obtain the tension of the visible brane for the above two solutions. When $N = N_{\text{min}} = 2n$, the visible brane tension is zero. For $r = r_1$ it is negative while for $r = r_2$ it is positive.

B. dS Brane:

For the induced brane cosmological constant $\Omega > 0$ the warp factor turns out to be:

$$e^{-A} = \omega \sinh \left( \ln \frac{c_2}{\omega} - ky \right) ,$$  \hspace{1cm} (2.5)

where $\omega^2 \equiv \Omega/3k^2$ and $c_2 = 1 + \sqrt{1 + \omega^2}$. In this case there is no bound on the value of $\omega^2$, and the (positive) cosmological constant can be of arbitrary magnitude. Also, there is
a single solution of $nr\pi$ whose precise value will depend on $\omega^2$ and $n$. The brane tension is negative for the entire range of values of the positive cosmological constant. In Fig.(1) it has been shown how the value of $\omega^2$ is related to the modulus which solves the hierarchy problem.

Moreover it has been shown in [2] that if one wants to resolve the fine tuning problem in connection with Higgs mass without introducing any intermediate scale through the modulus $r$ (i.e. keeping it close to Planck length) or the parameter $k$ (keeping it close to Planck mass) then the cosmological constant must be tuned to a very tiny value. Therefore the issues of gauge hierarchy problem and the cosmological constant problem are intimately related to each other. An interesting outcome of this generalised RS model has been found in the context of localization of fermions on the TeV brane [3]. It has been shown that although the generalised RS model allows different values of $kr$ for different values of the cosmological constant (both in dS and AdS region in the figure above) for the resolution of the hierarchy problem but the simultaneous requirement of fermion localization can be achieved only for vanishingly small cosmological constant i.e. when the warp factor is close to that obtained in the original RS model.

With this generalised RS braneworld model we now explore the mechanism of stabilizing the modulus $r$ to a desired value (which of course depend on the value the cosmological constant $\omega$) so that the desired Planck to TeV scale warping can be achieved.

III. STABILITY MECHANISM

To stabilize the modulus $r$ we adopt the method proposed by Goldberger and Wise [4] in the context of the original RS model. Let us consider a scalar field, $\Phi$ in the bulk with quartic interactions localized in the visible ($y = r\pi$) and Planck ($y = 0$) brane for which the bulk action turns out to be:

$$S = \frac{1}{2} \int d^4x \int_0^{r\pi} dy (G^{AB} \partial_A \Phi \partial_B \Phi - m^2 \Phi^2) + S_h \delta(y) + S_v \delta(y - r\pi)$$  \hspace{1cm} (3.1)

where $G_{AB}$ with $A, B = \mu, y$ is given by the metric (2.1) and the interaction terms on
FIG. 1: Graph of $N$ versus $x = kr\pi = 36 - 40$, for $n = 16$ and for both positive and negative brane cosmological constant. The curve in region-I corresponds to positive cosmological constant on the brane, whereas the curve in regions-II & III represents negative cosmological constant on the brane.

The hidden and visible branes are given by

$$S_h = -\int d^4x \sqrt{-g_h} \lambda_h (\Phi^2 - v_h^2)$$

$$S_v = -\int d^4x \sqrt{-g_v} \lambda_v (\Phi^2 - v_v^2)$$

Here $g_h$ and $g_v$ are the determinants of the induced metric on the hidden and visible brane respectively. The vacuum expectation values are given by $v_h$ and $v_v$ which have mass dimension 3/2 and $\lambda_h$ and $\lambda_v$ stands for the brane tensions. For simplicity we assume that the scalar field is a function of the extra dimension $y$ only. The equation of motion satisfied by the field $\Phi(y)$ is given by,

$$\partial_y(e^{-4A(y)}\partial_y \Phi) - e^{-4A(y)} \left( m^2 + 4\lambda_v \Phi(\Phi^2 - v_v^2)\delta(y - r\pi) + 4\lambda_h \Phi(\Phi^2 - v_h^2)\delta(y) \right) = 0$$

Now we study the nature of the solution of the scalar field for the warp factor given in (2.2). It has been discussed in the previous section that to resolve the gauge hierarchy problem without introducing any intermediate scale, the brane cosmological constant must be tuned to a very small value. Moreover the present observed value of the cosmological constant is also extremely tiny. We therefore consider small $\omega$ limit to solve the scalar field equation.

In this case the warp factor in (2.2) takes the following perturbative form

$$e^{-4A(y)} = e^{-4ky} + \omega^2 e^{-2ky}$$
With the above warp factor the scalar field equation away from the brane locations (i.e. inside the bulk) reduces to the following form:

$$\partial_y^2 \Phi - 4k \partial_y \Phi + 2k \omega^2 e^{2ky} + m^2 \Phi = 0$$

(S.6)

Solving the above equation we obtain the solution for the scalar field as,

$$\Phi(y) = e^{2ky} \left[ A e^{\nu ky} + B e^{-\nu ky} \right]$$

$$- \frac{\omega^2}{2} \left[ \hat{A} \left( \frac{\omega}{\sqrt{2}} \right)^\nu \left( \frac{\nu + 2}{\nu + 1} \right) e^{(\nu+1)ky} + \hat{B} \left( \frac{\omega}{\sqrt{2}} \right)^\nu \left( \frac{-\nu + 2}{-\nu + 1} \right) e^{(-\nu+1)ky} \right]$$

(S.7)

where \( \nu = \sqrt{4 + m^2 / k^2} \).

In the above solution we have defined \( A = \hat{A} \left( \frac{\omega}{\sqrt{2}} \right)^\nu \) and \( B = \hat{B} \left( \frac{\omega}{\sqrt{2}} \right)^\nu \) where \( \hat{A} \) and \( \hat{B} \) are arbitrary constants. The constants can be evaluated by using the appropriate boundary conditions at the locations of the branes.

An effective potential \( (V_{\text{eff}}) \) for the modulus \( r \) can now be obtained by putting the above solution (S.7) back into the scalar field action and integrating the entire scalar field action (S.1) over the extra dimension [4]. This yields an effective modulus potential as,

$$V_{\text{eff}} = k A^2 (\nu + 2) (e^{2\nu kr \pi} - 1) + k B^2 (2 - \nu) (e^{-2\nu kr \pi} - 1)$$

$$+ k \omega^2 2A^2 \left( \frac{\nu + 2}{\nu + 1} \right) (1 - e^{(2\nu + 2)kr \pi})$$

$$+ 2B^2 \left( \frac{2 - \nu}{1 - \nu} \right) (1 - e^{-(2-2\nu)kr \pi}) + AB \frac{\nu}{1 - \nu^2} (e^{2kr \pi} - 1)$$

$$+ \lambda_v e^{-4A} (\Phi(\pi)^2 - v_v^2) + \lambda_h (\Phi(0)^2 - v_h^2)$$

(S.8)

We now calculate the unknown coefficients \( A \) and \( B \). Rather than solving the equations in general (i.e. putting the solution back in the action and matching the delta functions) we consider the simplified case where the parameters \( \lambda_v \) and \( \lambda_h \) are large [4]. It is seen from the expression (S.8) that in this limit it is energetically favorable to have \( \Phi(0) = v_h \) and \( \Phi(\pi) = v_v \). For large \( kr \) limit the expressions for \( A \) and \( B \) turn out to be,

$$A = v_v e^{(2+\nu)kr \pi} - v_h e^{-2\nu kr \pi}$$

$$+ \frac{\omega^2}{2} v_h \left( \frac{2\nu}{1 - \nu^2} - \frac{2 + \nu}{1 + \nu} \right) e^{-2\nu kr \pi} + \frac{2(2 - \nu^2)}{1 - \nu^2} e^{(2-2\nu)kr \pi}$$

$$+ \frac{\omega^2}{2} v_v \left( \frac{2 + \nu}{1 + \nu} \right) e^{-\nu kr \pi}$$

(S.9)
and

\[ B = v_h \left( 1 + e^{-2\nu kr\pi} \right) - v_v e^{-(2+\nu)kr\pi} \]
\[ + \frac{\omega^2}{2} v_h \left[ \left( \frac{2\nu}{1 - \nu^2} \right) + \left( \frac{2 + \nu}{1 + \nu} \right) \right] \left( 1 + e^{-2\nu kr\pi} \right) - \frac{2(2 - \nu^2)}{1 - \nu^2} e^{(2-\nu)kr\pi} \]
\[ - \frac{\omega^2}{2} v_v \left[ \left( \frac{2\nu}{1 - \nu^2} \right) e^{-(\nu+2)kr\pi} + \left( \frac{2 + \nu}{1 + \nu} \right) e^{-\nu kr\pi} \right] \]  

(3.10)

where subleading powers of \( e^{-kr\pi} \) have been neglected. Now suppose that \( m/k \ll 1 \) so that \( \nu = 2 + \epsilon \), with \( \epsilon \simeq m^2/4k^2 \) is a small quantity. In the large \( kr \) limit, the expression of the potential becomes,

\[ V_{eff} = (4 + \epsilon)e^{-4\nu kr\pi} (v_v - v_h e^{-\epsilon kr\pi})^2 + (4 + \epsilon)e^{-4\nu kr\pi} 2\omega^2 (v_v - v_h e^{-\epsilon kr\pi})(v_v F(k) + v_h e^{-\epsilon kr\pi} G(k)) \]
\[ - \omega^2 \frac{2(4 + \epsilon)}{3 + \epsilon} (v_v - v_h e^{-\epsilon kr\pi})^2 e^{-2kr\pi} + \epsilon \left[ v_h^2 (1 + e^{-2(2+\epsilon)kr\pi}) - 2v_v v_h e^{-(4+\epsilon)kr\pi} \right] \]
\[ + 2\omega^2 \epsilon \left[ v_h^2 \left( 1 + e^{-2(2+\epsilon)kr\pi} \right) P(k) + v_v e^{-(4+\epsilon)kr\pi} (v_v Q(k) - v_h (P(k) + Q(k))) \right] \]
\[ + \epsilon \left[ v_h^2 \left( 1 + e^{-2(2+\epsilon)kr\pi} - e^{(2-4(2+\epsilon))kr\pi} - 2e^{(2-4(2+\epsilon))kr\pi}) \right) - 2v_v v_h e^{-(4+\epsilon)kr\pi} \right] \]
\[ + \left( \frac{2 + \epsilon}{3 + 4\epsilon} \right) v_v^2 e^{-2(4+\epsilon)kr\pi} \left[ 1 + \omega^2 (F(k) + Q(k)) \right] + v_h^2 e^{-(4+\epsilon)kr\pi} \left[ 1 + \omega^2 (P(k) - G(k)) \right] \]
\[ - v_v v_h e^{-(4+\epsilon)kr\pi} \left[ 1 + \omega^2 (P(k) + F(k)) + e^{-(4+\epsilon)kr\pi} (1 + \omega^2 (Q(k) - G(k)) \right] \]  

(3.11)

where terms of order \( \epsilon^2 \) are neglected but \( \epsilon kr \) is not treated as small. The quantities P, Q, F and G are given by

\[ 2P(k) = \left( \frac{2\nu}{1 - \nu^2} \right) + \left( \frac{2 + \nu}{1 + \nu} \right) - \left( \frac{2(2 - \nu^2)}{1 - \nu^2} \right) e^{(2+\epsilon)kr\pi} \]  

(3.12)

\[ 2Q(k) = \left( \frac{2\nu}{1 - \nu^2} \right) + \left( \frac{2 + \nu}{1 + \nu} \right) e^{2kr\pi} \]  

(3.13)

\[ 2F(k) = \left( \frac{2 + \nu}{1 + \nu} \right) e^{2kr\pi} \]  

(3.14)

\[ 2G(k) = \left( \frac{2\nu}{1 - \nu^2} \right) - \left( \frac{2 + \nu}{1 + \nu} \right) + \left( \frac{2(2 - \nu^2)}{1 - \nu^2} \right) e^{2kr\pi} \]  

(3.15)

Ignoring the terms proportional to \( \epsilon \) we obtain the following conditions for which one achieve the minima of the potential

\[ 4(v_v - v_h e^{-\epsilon kr\pi}) - \frac{\omega^2}{3} e^{2\nu kr\pi} (4v_v - 11v_h e^{-\epsilon kr\pi}) = 0 \]  

(3.16)

It may be clearly seen from the equation \( 3.16 \) that for \( \omega = 0 \), the potential has a minima at

\[ kr = \frac{1}{\epsilon\pi} \ln(v_h/v_v) \]  

(3.17)
which is identical to the solution of the Goldberger and Wise. Note that due to the presence of a non-zero brane cosmological constant the modified minima is obtained from (3.16) as

\[ kr = \frac{1}{\epsilon \pi} \ln(v_h/v_v) - \frac{7\omega^2}{12\epsilon \pi}(v_h/v_v)^{2/\epsilon} \]  
(3.18)

This result brings out an interesting feature. We know for \( \omega = 0 \) (i.e. RS case), a suitable non-hierarchical choice for \((v_h/v_v)\) yields a stable value of \(kr\) which is same as that proposed by Randall and Sundrum to resolve the gauge hierarchy problem. However from the figure (1), it can be seen that as we move into the Anti-de-Sitter region from \(\omega^2 = 0\) (i.e. RS case) by increasing the magnitude of \(\omega^2\) slightly, the required value of \(kr\) (to resolve the gauge hierarchy problem) increases from RS value. On the other hand the corresponding stabilized value of \(kr\) decreases with increase in \(\omega^2\), as has been shown in (3.18). This opposite behavior clearly indicates that to achieve modulus stabilization and resolution of gauge hierarchy problem simultaneously the most favored value of the brane cosmological constant \(\omega = 0\) which was proposed in the original model.

The entire stability analysis done so far is based on the AdS brane background. If one performs the same study with dS brane warp factor given in (2.5) we end up with the conditions,

\[ 4(v_v - v_h e^{-kr\pi}) + \frac{\omega^2}{3} e^{2kr\pi} (4v_v - 11v_h e^{-kr\pi}) = 0. \]  
(3.19)

with the stable modulus value as,

\[ kr = \frac{1}{\epsilon \pi} \ln(v_h/v_v) + \frac{7\omega^2}{12\epsilon \pi}(v_h/v_v)^{2/\epsilon} \]  
(3.20)

Once again the figure[11] and (3.20) reveals that while the required value of \(kr\) which resolves the gauge hierarchy problem, decreases with increase in the value of positive brane cosmological constant \(\omega^2\), the corresponding stabilized value increases with \(\omega^2\). Thus once again RS assumption of \(\omega^2 = 0\) turns out to be a most favored solution.

**IV. CONCLUSION**

We now summarize the results obtained in this work. We have shown that for a generalized RS model with a cosmological constant on the brane, the modulus stabilization condition explicitly depends on the brane cosmological constant. We have obtained this condition both for positive and negative values of the brane cosmological constant. It turns
out that if one increases the magnitude of $\omega^2$ from zero the stabilized value of $kr$ decreases (increases) for AdS (dS) brane. Whereas the value of $kr$ which solves the hierarchy problem increases (decreases) with the increase in value of the cosmological constant. It implies that if one starts from $\omega^2 \sim 0$, then the variation of $kr$ with $\omega^2$ for the requirement modulus stabilization and that for the gauge hierarchy resolution are opposite. This establishes that while the generalized RS model indeed predicts that for every value of brane cosmological constant we have a corresponding value of $kr$ which can resolve the problem of gauge hierarchy, the zero value of the brane cosmological constant, as assumed in the original RS model is most favored if one imposes in addition the condition of modulus stabilization. The present small value of $\omega^2 \sim 10^{-124}$ yields the stabilized value of $kr$ for the de-Sitter case (see equ. 3.20), which is very close to the corresponding value of $kr$ needed to resolve the gauge hierarchy problem (see Figure 1). However for larger value of $\omega^2$ the stabilized value of $kr$ is further away from that required to resolve the gauge hierarchy problem. Thus a non-zero cosmological constant on the brane can consistently address both the gauge hierarchy as well as the modulus stabilization problem only when it’s value is extremely tiny. This is in agreement with the anthropic explanation [10] in favour of a small cosmological constant of our universe.

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