We investigate the Ricci Dark Energy (RDE) in the braneworld models with a Gauss-Bonnet term in the Bulk. We solve the generalized Friedmann equation on the brane analytically and find that the universe will finally enter into a pure de Sitter spacetime in stead of the big rip that appears in the usual 4D Ricci dark energy model with parameter $\alpha < \frac{1}{2}$. We also consider the Hubble horizon as the IR cutoff in holographic dark energy model and find it can not accelerate the universe as in the usual case without interacting.

The current observations such as SNeIa, CMB and SDSS et al. have strongly confirmed that our universe is accelerated expanding. However, according to the Newton’s gravity theory, ordinary matters can only attract each other, so the universe should be decelerated expanding. Therefore, there must be something unknown that exists in the universe, and they are often called dark energy. Experiments indicate that there are mainly about 73% dark energy and 27% matter components in the recent universe, but people still do not understand what is dark energy from fundamental theory currently.

The cosmology constant which can only appears in the Einstein equation without ruining the Bianch identity seems the best candidate for dark energy, but it suffers from the fine-tuning and coincident problems. The fine-tuning problem says why the vacuum energy density observed today is so much smaller than the value predicted by the quantum field theory, and we need to fine tune the cosmological constant to cancel it and get the observation value, while the coincidence problem is asking why it is today that dark energy becomes important, since its evolution behavior is so much different from that of ordinary matter. In order to alleviate these problems, a lot of dynamic dark energy models have been built, such as quintessence, phantom, quintom models which are basically scalar field models. Another way to explain the accelerating is to modify general gravity like $f(R)$ theory and DGP model, etc..

Actually, the cosmology constant (or dark energy) problem is in essence an issue of quantum gravity [1], since the energy density of dark energy is inevitably related to the large vacuum energy density of the quantum field theory without including gravity. Considering the gravity effects, there may be some regions in which the field theory is invalid. The holographic principle regards the black hole as the object with maximum entropy in a given region, and from statistical physics, the entropy is a extensive quantity which proportional to the volume of such region, while the black hole’ entropy is proportional to the area of its surface, so in the field theory, there should exists a infrared (IR) cutoff, beyond which the field theory will be failed. However, such constraint seems a little bit loose, because it includes the black hole state in the field theory. To avoid the existence of such states, Cohen et al. [2] suggested that in a given region with length scale $L$, the field’s energy should be bounded by the black hole’s, i.e. $\rho L^3 \leq L M_{pl}^2$, where $\rho$ is the total energy density within the region and $M_{pl} = G^{-1/2}$ is the Planck mass. Applying the holographic principle to cosmology, Li [3] has proposed the holographic dark energy model, in which the energy density of dark energy is $\rho = 3c^2 M_{pl}^2 L^{-2}$, namely it saturates the bound. He finds that when $L = R_h$, which is the future event horizon, this model will be consistent with observations and meanwhile solves the coincidence problem, and this model is often called HDE for short.

Although the holographic model based on the future event horizon is successful in fitting the current data, some authors asked why the current acceleration of the universe is determined by its future. Actually, the future event horizon is not the only choice for the holographic dark energy model. Also motivated by the holographic principle, Gao, et al. [4] have proposed the Ricci dark energy (RDE) model recently, in which the future event horizon area is replaced by the inverse of Ricci scalar, and this model is also phenomenologically viable.

Assuming the black hole is formed by gravitation collapsing of the perturbation in the universe, the maximal black hole can be formed is determined by the casual connection scale $R_{CC}$ given by the "Jeans" scale of the perturbations.
For tensor perturbations, i.e. gravitational perturbations, $R_{CC}^2 = Max(\dot{H} + 2H^2, -\dot{H})$ for a flat universe, and according to the ref. [3], only in the case of $R_{CC}^2 = \dot{H} + 2H^2$, it could be consistent with the current cosmological observations when the vacuum density appears as an independently conserved energy component. Therefore, if one chooses the casual connection scale $R_{CC}$ as the IR cutoff in the holographic dark energy, the Ricci dark energy model is also obtained. For recent progress on Ricci dark energy and holographic dark energy, see ref. [5][6][7][8][9][10].

In flat FRW universe, the Ricci scalar is $R_4 = 6(\dot{H} + 2H^2)$ and the energy density of RDE reads

$$\rho_R = 3\alpha \left( \dot{H} + 2H^2 \right) \propto R_4,$$

where we have set $8\pi G = 1$ and $H = \dot{a}/a$ is the Hubble parameter. Here $\alpha$ is a dimensionless parameter which will determine the evolution behavior of RDE.

In ref. [3], the author apply bulk holographic principle in general branewold models with a Gauss-Bonnet term in the bulk, and get an effective 4D holographic dark energy from 5D theory. They have also taken the 4D future event horizon as the IR cutoff to study the behaviors of the dark energy. In this letter, we investigate the RDE model in this braneword model and find that the RDE model which behaviors like a quintom with parameter $\alpha < 1/2$ and dominates the universe in the future will lead the universe to enter into the pure de Sitter spacetime instead of the big rip in the far future. Early works on dark energy models with late time de Sitter attractor, see ref. [11].

The 5D braneworld models with a Gauss-Bonnet term in the bulk can be described by the following action [3]:

$$S = \int d^4x \sqrt{-g} (M_5^3 R - \rho_{\Lambda 5} + \beta M_5 \mathcal{L}_{GB}) + \int d^4x \sqrt{-\gamma} (\mathcal{L}_{\text{brane}}^{\text{mat}} - V + r_c M_5^3 R_4),$$

where $M_5$ is the 5D Planck mass, $\rho_{\Lambda 5}$ is the bulk cosmological constant, and $R$ is the curvature scalar of the 5D bulk spacetime with metric $g_{AB}$. As usual, the Gauss-Bonnet lagrangian is

$$\mathcal{L}_{\text{GB}} = R^2 - 4R_{AB}R^{AB} + R_{ABCD}R^{ABCD}$$

with coupling constant $\beta$, and $R_{ABCD}$, $R_{AB}$ are the Riemann tensor and Ricci tensor respectively. In the second integral, $\gamma = \det g_{\alpha\beta}$ is the induced 4D metric, $V$ is the brane tension and $\mathcal{L}_{\text{brane}}^{\text{mat}}$ is an arbitrary brane matter content. The last term is arisen from radiative corrections, with $r_c$ its characteristic length scale and $R_4$ the 4D Ricci scalar. By using the Gaussian normal coordinates with the metric:

$$ds^2 = -n^2(\tau, y)d\tau^2 + a^2(\tau, y)d\Omega^2_k + dy^2,$$

we can imposed a $Z_2$-symmetry around the brane located at $y = 0$, i.e. $n(\tau, y = 0) = 1$ to get a cosmology evolution on the brane. Here $d\Omega^2_k$ denotes the metric in a maximally symmetric 3-dimensional space with $k = -1, 0, +1$ parameterizing its spacial curvature. Matters on the brane are regarded as perfect fluids with equation state $p = w\rho$. After integration of the 00 and $ii$ components of the 5D Einstein equations around the brane, we get the brane cosmology evolution equations in the low-energy limit $\rho \ll V$ as in [3]:

$$H^2 + \frac{k}{a^2} = \left( \frac{72M_5^6 - 16\beta \rho_{\Lambda 5} M_5^3 + 6r_c VM_5^3}{144M_5^6} \right)^{-1} V \rho + \frac{V^2}{144M_5^6} - \frac{1 - \sqrt{1 + \Lambda}}{36\beta} \left( 2 + \sqrt{1 + \Lambda} \right)^2$$

where $\Lambda = 2\beta \rho_{\Lambda 5} / (3M_5^3)$. Here $\alpha$ is the scale factor on the brane. In order to be consistent with conventional 4D Friedmann equation, one has to impose:

$$V = \frac{192\pi M_5^6}{M_5^2 - 16r_c M_5^3}.$$  

Then the evolution equation (5) becomes:

$$H^2 + \frac{k}{a^2} = \frac{8\pi \rho}{3M_5^2} \left( 1 + V_1(\beta, \rho_{\Lambda 5}) \right) + \frac{8\pi}{3M_5^2} \rho_{\Lambda},$$

where $V_1$ is defined as

$$V_1(\beta, \rho_{\Lambda 5}) = \frac{128\pi \beta \rho_{\Lambda 5}}{3VL_5 - 128\pi \beta \rho_{\Lambda 5}},$$
and here we have used the relation between the 5D and 4D Planck mass $M_5^3 = M_p^2 L_5^{-1}$, where $L_5$ is the size of the extra dimension. The 4D effective dark energy $\rho_\Lambda \equiv \rho_\Lambda^{eff}$ in eq.\,(7) is:

\[
\rho_\Lambda = \frac{96\pi M_p^2}{(L_5 - 16\pi r_c)^2} - \frac{M_p^2}{96\pi^2} \left( 1 - \sqrt{1 + \Lambda} \right) \left( 2 + \sqrt{1 + \Lambda} \right)^2
\]  

(9)

A $D$-dimensional spherical and uncharged black hole with mass $M_{BH}$ as

\[
M_{BH} = r_s^{D-3} (\pi)^{D-1} (M_D)^{D-2} \frac{D - 2}{8\Gamma(\frac{D-2}{2})},
\]  

(10)

where $r_s$ is its Schwarzschild radius and $M_D$ is $D$-dimensional Planck mass, namely $(M_D)^{D-2} = G_D^{-1}$ and it relates to the usual 4-dimensional Planck mass $M_p$ by $M_p^2 = (M_D)^{D-2} V_{D-4}$, where $V_{D-4}$ is the volume of the extra-dimensional space. Let $\rho_{AD}$ is the vacuum energy in the bulk and by applying $D$-dimensional holographic principle we obtain:

\[
\rho_{AD} \text{Vol}(S^{D-2}) \leq r^{D-3}(\pi)^{D-1} (M_D)^{D-2} \frac{D - 2}{8\Gamma(\frac{D-2}{2})},
\]  

(11)

where $\text{Vol}(S^{D-2})$ is the volume of the maximal hypersphere in a $D$-dimensional spacetime, and it reads $\text{Vol}(S^{D-2}) = A_D r^{D-1}$ with

\[
A_D = \frac{\pi^{D-1}}{(\frac{D-2}{2})!}, \quad A_D = \frac{(D-2)!}{(D-1)!} 2^{D-1} \pi^{D-1} \frac{D}{D-2},
\]  

(12)

for $D-1$ being even or odd respectively. Therefore, by saturating inequality\,(11), we get the $D$-dimensional holographic dark energy as

\[
\rho_{AD} = c^2 (\pi)^{D-1} (M_D)^{D-2} A_D^{-1} \frac{D - 2}{8\Gamma(\frac{D-2}{2})} L^{-2}.
\]  

(13)

Therefore, the 5D holographic dark energy is given by:

\[
\rho_{\Lambda 5} = 3c^2 \frac{1}{4\pi} M_5^3 L^{-2}.
\]  

(14)

Hereafter, we will use the assumption in ref.\,[8] that $L_5$ is arbitrary large finitely, namely, it is larger than any other length of this model leaving the brane evolution independent of the size of the bulk and this is the reason for the single-brane consideration. So, we will use the approximation $L_5 \gg r_c$ and $L_5^{-1} \rightarrow 0$ in the calculation. Furthermore, we also expand relevant quantities in terms of the Gauss-Bonnet coupling $\beta$, and only keep linear terms, thus we obtain

\[
V_1(\beta, L) = \beta \frac{c^2}{6\pi} L^{-2} + O(\beta^2),
\]  

(15)

and the effective 4D energy density for the dark energy from\,[9]:

\[
\rho_\Lambda \equiv \rho_\Lambda^{eff} = 3c^2 \frac{1}{128\pi^2} M_p^2 L^{-2} \left( 1 + \beta \frac{c^2}{24\pi} L^{-2} \right) + O(\beta^2).
\]  

(16)

Comparing with the result directly derived from eq.\,(13):

\[
\rho_\Lambda = \frac{3c^2}{8\pi} M_p^2 L^{-2},
\]  

(17)

where one can see the effective dark energy $\rho_\Lambda^{eff}$ is smaller than $\rho_\Lambda$ for the same IR cutoff $L$, which means the dark energy derived from 5D holographic principle is stringent than the one directly from 4D. Therefore, we get the Friedmann equation for flat brane universe under these approximation:

\[
3H^2 = \rho \left( 1 + \frac{8}{3} \beta_\alpha L^{-2} \right) + 3\alpha L^{-2} \left( 1 + \frac{2}{3} \beta_\alpha L^{-2} \right),
\]  

(18)
where we have set $8\pi M_p^2 = 1$ and $\alpha \equiv c^2/(16\pi)$ for convenience. When $\beta \to 0$, the above equation return to the result in ref.\[4\]. Here one can see, there is interacting terms between dark energy and ordinary matter, and it arises naturally from the 5D dynamics and the use of holographic principle in the bulk, rather than putting by hand like interacting dark energy. The IR cutoff $L$ could be Hubble horizon, particle horizon or future event horizon etc. and there is no first principle to judge which cutoff is correct. Therefore, the only way to check these IR cutoff is by the observations. As we mentioned above, once the 5D holographic principle is satisfied, it should be also satisfied in 4D, because the derived effective dark energy \[16\] from 5D bulk is stringed than that \[17\] from 4D itself. Therefore, we would like to identify the IR cutoff $L$ to the "Jeans-like" causal connection length scale $R_{CC}$, beyond which the black hole can not formed by gravitational collapse of perturbation in the universe. For gravitational perturbation and not conflict with experiments, $R_{CC}^2 = H + 2H^2$ is the only choice for 4D flat universe. By taking the $R_{CC}$ as the IR cutoff in eq.\[17\], the Ricci dark energy model is obtained, but here we will using the effective 4D dark energy \[16\] to study the Ricci dark energy in the braneworld models.

Before investigating the Ricci dark energy in this model, we would like to taking a simple choice $L = H^{-1}$, and in this case, we shall see that it can not make the universe accelerating. The Friedmann equation \[18\] can be rearranged:

$$2\alpha\beta (\alpha H^2)^2 + \left(3\alpha + \frac{8}{3}\alpha\beta \rho - 3\right) \alpha H^2 + \alpha \rho = 0,$$

and the solution to this equation is the following:

$$H^2 = \frac{\rho}{3(1-\alpha)} + \frac{2\alpha(4-3\alpha)\rho^2}{27(1-\alpha)^3} \beta,$$

where we have kept the linear term of $\beta$ only. Applying the energy conservation equation and assuming only matters (pressureless) resides on the brane universe, we get $\rho_m = \rho_{m0}(a/a_0)^{-3}$, where the subscript $0$ denotes the present value of the quantity. Therefore, we get the evolution of the universe on the brane:

$$a(\tau) = a_0 \left(C_0 \tau^{\frac{2}{3}} + C_1 \beta \tau^{-\frac{1}{3}} \right),$$

where

$$C_0 = \left[\frac{3\rho_{m0}}{4(1-\alpha)}\right]^{\frac{1}{3}}, \quad C_1 = \frac{2\pi}{3\sqrt{3}} \frac{(4-3\alpha)\alpha}{(1-\alpha)^2} \beta \rho_{m0}.$$  \hspace{1cm} (22)

Thus, one can see the first term on the rhs. of eq.\[21\] is much like the usual evolution of matter dominated universe, while the second one is the correction from the Gauss-Bonnet term. The energy density of the effective 4D dark energy is

$$\rho_\Lambda = \frac{\alpha \rho}{1-\alpha} + \frac{2\alpha^2(5-4\alpha)\rho^2}{9(1-\alpha)^3} \beta,$$

and the its equation of state parameter is

$$w \equiv -1 - \frac{1}{3} \frac{d \ln \rho_\Lambda}{d \ln a} = \frac{2\alpha(5-4\alpha)\rho_{m0}}{9(1-\alpha)^2} \beta (1+z)^3 > 0.$$  \hspace{1cm} (24)

So, the universe is not accelerated expanding and $L = H^{-1}$ is not a good choice for IR cutoff in this sense.

Now, we will identify $L^{-2} = R_{CC}^2 = H + 2H^2$ in flat universe, then the Friedmann equation \[18\] becomes:

$$\left(2\beta\alpha^2 H^2\right)Y^2 + \left(8/3\rho \beta \alpha + 3\alpha\right)Y + \rho H^{-2} - 3 = 0,$$

where we have defined $Y \equiv (R_{CC}H)^{-2}$, and by solving this equation we get:

$$Y = \frac{3 - \rho H^{-2}}{3\alpha} - \frac{6H^2 + 4\rho - 2\rho^2 H^{-2}}{9\alpha} \beta,$$

up to the linear term of $\beta$. Replacing $YH^2 = (H^2)^2/2 + 2H^2$ and $\rho = \rho_{m0}e^{-3x}$ we get the differential equation for the Hubble parameter as follows:
where $\rho_m = \rho_m(3H_0^2)$ and we have defined dimensionless coupling $\tilde{\beta} = H_0^2\beta$. Hereafter, prime denotes the derivative with respect to $x \equiv \ln a$. Substituting

$$u(x) = \exp \left[ \frac{4\tilde{\beta}}{3\alpha} \int h^2 dx + \left(4 - \frac{2}{\alpha}\right)x \right]$$

reduce the eq. (27) to a second-order linear equation of $u$:

$$9\xi \frac{d^2 u}{d\xi^2} + \left( -\frac{8\Omega_m\tilde{\beta}}{\alpha} \xi + 21 - \frac{6}{\alpha} \right) \frac{du}{d\xi} + \frac{8\Omega_m\tilde{\beta}}{3\alpha} \left( -\frac{2\Omega_m\tilde{\beta}}{\alpha} \xi - 4 + \frac{3}{\alpha} \right) u = 0,$$

where $\xi = e^{-3x}$ and the solution to this equation is

$$u(\xi) = _1F_1 \left( \frac{13}{12}, \frac{7}{3}, \frac{2}{3}, -\frac{16\Omega_m\tilde{\beta}}{9\alpha} \xi \right) \exp \left( \frac{4\Omega_m\tilde{\beta}}{3\alpha} \xi \right),$$

where $_1F_1$ is the Kummer confluent hypergeometric function. When $x \to \infty$, i.e. $\xi \to 0$, the Kummer function $_1F_1 \approx 1$, and also $u(\xi) \approx 1$, thus we obtain the final value of the Hubble parameter

$$h(x \to \infty) \approx \sqrt{\frac{3(1-2\alpha)}{2\beta}}.$$  

Therefore, if $\tilde{\beta} = 0$, which means no Gauss-Bonnet term in the action (28), the Hubble parameter will become infinite in the future. And it is due to the Gauss-Bonnet term that the big rip disappears and finally the energy density of the dark energy is

$$\rho_\Lambda(x \to \infty) \approx 3\alpha \left( 1 - 8\alpha^2 + 8\alpha^3 \right) \frac{\rho_c}{\beta},$$

where $\rho_c \equiv 3H_0^2$ is the critical energy density today. According the holographic principle, the UV cutoff satisfy $\Lambda^2 \leq L^{-1}M_p$, and the inverse of IR cutoff $L^{-1}$ should be smaller than the UV cutoff by definition, i.e. $L^{-1} < \Lambda$, so $\Lambda < M_p$. Therefore, it requires

$$\tilde{\beta} \gtrsim \frac{\rho_c}{M_p^2} \sim 10^{-120} \quad \text{or} \quad \beta \gtrsim l_p^2,$$

where $l_p$ is the Planck length. To illustrate and double check our analytical solution, we also give an example of numerical calculation in Fig.1, from which one can see the effect of the Gauss-Bonnet term as follows: when $\tilde{\beta} = 0$, we recover the usual Ricci dark energy in ref.[3], then it shows the Hubble parameter will blow up in finite time, which means there will be a big rip in some time. However, the actually framework of the holographic model of dark energy is the effective field theory with an UV/IR duality. Before the big rip, the UV cutoff of the theory will exceed the Planck energy scale, and this will definitely spoil the effective field theory. Therefore, in the holographic model of dark energy, the big rip is actually not allowed. Now, with the help of the Gauss-Bonnet term, the universe will finally enter into the steady state (de Sitter) space instead of the big rip, see Fig.1. If the parameter $\alpha \geq 1/2$, there is no big rip time in the later time with or without the Gauss-Bonnet term, see the right one in Fig.1.

In ref.[7], the author generalized the IR cutoff for holographic dark energy as $L^{-2} \sim \gamma H^2 + \lambda H$, where $\gamma$ and $\lambda$ are constants. When $\gamma \lambda^{-1} = 2$, it reduces to RDE. By taking $Y = \dot{H}H^{-2} + \gamma\lambda^{-1}$ and from eq. (30), we obtain

$$\frac{(h^2)'}{2} + \frac{(\gamma - 1)}{\lambda} h^2 + \frac{\Omega_m e^{-3x}}{\lambda} + \frac{2h^4 + 4h^2\Omega_m e^{-3x} - 6(\Omega_m e^{-3x})^2}{3\lambda} \tilde{\beta} = 0.$$  

Substituting

$$v(x) = \exp \left[ \frac{4\tilde{\beta}}{3\lambda} \int h^2 dx + \left(\frac{2(\gamma - 1)}{\lambda}\right)x \right]$$

reduce the eq. (34) to a second-order linear equation of $v$:
FIG. 1: Evolution of $h(x)$ with initial condition $h(0) = 1$ and $\Omega_{m0} = 0.27$. The left figure is plotted with $\alpha = 0.36$ and $\tilde{\beta} = 0$ (solid curve), 0.001 (dotted curve), 0.002 (dashed curve), 0.003 (dot-dashed curve), and it shows the Hubble parameter will blow up in sometime without the Gauss-Bonnet term ($\tilde{\beta} = 0$) while the universe will finally enter into the de Sitter space with the help of the Gauss-Bonnet term ($\tilde{\beta} \neq 0$). The right figure indicates is plotted with $\tilde{\beta} = 0.01$ and $\alpha = 0.36$ (solid curve), 0.5 (dashed curve), 0.6 (dot-dashed curve), while the horizon dot-dashed line corresponds $h(x) = -1$.

\[
9\xi \frac{d^2 v}{d\xi^2} + \left( -\frac{8\Omega_{m0}\tilde{\beta}}{\lambda} \xi + 9 + \frac{6(\gamma - 1)}{\lambda} \right) \frac{du}{d\xi} + \frac{8\Omega_{m0}\tilde{\beta}}{3\lambda} \left( -\frac{2\Omega_{m0}\tilde{\beta}}{\lambda} \xi + \frac{3 - 2\gamma}{\lambda} \right) v = 0, \tag{36}
\]

and its solution is

\[
v(\xi) = _1F_1 \left( \frac{3}{4} + \frac{\gamma}{6\lambda}, 1 + \frac{2(\gamma - 1)}{3\lambda}, -\frac{16\Omega_{m0}\tilde{\beta}}{9\lambda} \xi \right) \exp \left( \frac{4\Omega_{m0}\tilde{\beta}}{3\lambda} \xi \right), \tag{37}
\]

and we also get the finally value of Hubble parameter:

\[
h(x \to \infty) \approx \sqrt{\frac{3(1 - \gamma)}{2\tilde{\beta}}}. \tag{38}
\]

Again, the universe will enter into de Sitter spacetime instead of the big rip in the far future. Then, the energy density of dark energy at that time will be

\[
\rho_\Lambda(x \to \infty) \approx \frac{3\gamma}{2} \left( 1 - 2\gamma^2 + \gamma^3 \right) \frac{\rho_c}{\tilde{\beta}}, \tag{39}
\]

and it also requires $\tilde{\beta} \gtrsim \rho_c M_p^{-4}$ or $\beta \gtrsim l_p^2$.

In conclusion, we have investigate the Ricci dark energy in the framework of 5D braneworld models with a Gauss-Bonnet term in the bulk. Due to the effect of the Gauss-Bonnet term, the universe will avoid the big rip problem that appears in the usual Ricci dark energy with parameter $\alpha < 1/2$. In that case, the universe will finally dominated by the Ricci dark energy and the scale factor will becomes infinity in finite time, while in our result, the universe will enter into the de Sitter space in the far future instead of the big rip. Since the holographic Ricci dark energy is basically the effective field theory with UV/IR duality, the big rip seems inconsistent with the theoretical framework, therefore the story of Ricci dark energy in the braneworld model with a Gauss-Bonnet term sounds interesting and is deserved to be studied further.

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