Interacting holographic tachyon model of dark energy

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We propose a holographic tachyon model of dark energy with interaction between the components of the dark sector. The correspondence between the tachyon field and the holographic dark energy densities allows the reconstruction of the potential and the dynamics of the tachyon scalar field in a flat Friedmann-Robertson-Walker universe. We show that this model can describe the observed accelerated expansion of our universe with a parameter space given by the most recent observational results.

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I. INTRODUCTION

Recent cosmological observations from Type Ia supernovae (SN Ia) [1], Cosmic Microwave Background (CMB) anisotropies measured with the WMAP satellite [2], Large Scale Structure [3], weak lensing [4] and the integrated Sach-Wolfe effect [5] provide an impressive evidence in favor of a present accelerating Universe. Within the framework of the standard Friedmann-Robertson-Walker (FRW) cosmology, this present acceleration requires the existence of a negative pressure fluid, dubbed dark energy (DE), whose pressure p_Λ and density ρ_Λ satisfy $\omega_\Lambda = p_\Lambda/\rho_\Lambda < -1/3$. In spite of this mounting observational evidence, the underlying physical mechanism behind this phenomenon remains unknown. Interesting proposals are the quantum cosmic model [6] and $f(R)$ theories (see [7] for recent reviews and references therein). Likewise, we have a plethora of dynamical dark energy models [8].

On the other hand, based on the validity of effective local quantum field theory in a box of size L, Cohen et al [9] suggested a relationship between the ultraviolet (UV) and the infrared (IR) cutoffs due to the limit set by the formation of a black hole. The $UV - IR$ relationship gives an upper bound on the zero point energy density,

$$\rho_\Lambda \leq L^{-2} M_p^2, \tag{1}$$

where L acts as an IR cutoff and M_p is the reduced Planck mass in natural units. This means that the maximum entropy in a box of volume L^3 is

$$S_{max} \approx S_{BH}^{3/4}, \tag{2}$$

being S_{BH} the entropy of a black hole of radius L. The largest L is chosen by saturating the bound in Eq. (1) so that we obtain the holographic dark energy density

$$\rho_\Lambda = 3c^2 M_p^2 L^{-2}, \tag{3}$$

where c is a free dimensionless $\mathcal{O}(1)$ parameter and the numeric coefficient is chosen for convenience. Interestingly, this ρ_Λ is comparable to the observed dark energy density $\sim 10^{-10} eV^4$ for the Hubble parameter at the present epoch $H = H_0 \sim 10^{-33} eV$.

If we take L as the Hubble scale H^{-1}, then the dark energy density will be close to the observational result. However, Hsu [10] pointed out that this does not lead to an accelerated universe. This led Li [11] to propose that the IR cut-off L should be taken as the size of the future event horizon of the Universe

$$R_{\rm eh}(a) \equiv a \int_t^\infty \frac{dt'}{a(t')} = a \int_a^\infty \frac{da'}{Ha'^2}\ , \tag{4}$$

where a is the scale factor of the universe and t the cosmic time. Choosing the future event horizon as the UV cut-off tacitly assumes the acceleration of the expansion of the universe. Since the accelerating universe is a well supported observational fact, we believe that this assumption is plausible.

This allows to construct a satisfactory holographic dark energy (HDE) model which presents a dynamical view of the dark energy which is consistent with observational data [12]. As a matter of fact, a time varying dark energy gives a better fit than a cosmological constant according to some analysis of astronomical data coming from type Ia supernovae [13]. However, it must be stressed that almost all dynamical dark energy models are settled at the phenomenological level and the HDE model is no exception in this respect. Its advantage,

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when compared to other dynamical dark energy models, is that the HDE model originates from a fundamental principle in quantum gravity, and therefore possesses some features of an underlying theory of dark energy.

A further development was to consider a possible interaction between dark matter (DM) and the HDE [14].

It is usually assumed that both DM and DE only couple gravitationally. However, given their unknown nature and that the underlying symmetry that would set the interaction to zero is still to be discovered, an entirely independent behavior between the dark sectors would be very special indeed. Moreover, since DE gravitates, it must be accreted by massive compact objects such as black holes and, in a cosmological context, the energy transfer from DE to DM may be small but non-vanishing. In addition, it was found that an appropriate interaction between DE and DM can influence the perturbation dynamics and affect the lowest multipoles of the CMB angular power spectrum [15, 16]. Thus, it could be inferred from the expansion history of the Universe, as manifested in several experimental data. Furthermore it was suggested that the dynamical equilibrium of collapsed structures such as clusters would be modified due to the coupling between DE and DM [17, 18]. Most studies on the interaction between dark sectors rely either on the assumption of interacting fields from the outset [19, 20], or from phenomenological requirements [21]. The aforesaid interaction has also been considered from a thermodynamical perspective [22, 23] and has been shown that the second law of thermodynamics imposes an energy transfer from DE to DM.

As is well known, the scalar field models are an effective description of an underlying theory of dark energy. Scalar fields naturally arise in particle physics including supersymmetric field theories and string/M theory. However, these fundamental theories do not predict their potential $V(\phi)$ uniquely. Consequently, it is meaningful to reconstruct the potential $V(\phi)$ of a dark energy model possessing some significant features of the quantum gravity theory, such as the interacting HDE (IHDE) model.

In this Letter we would like to extend the previous work done by Zhang et al [24], where they took advantage of the successful HDE model and used the tachyon scalar field as an effective description of an underlying theory of dark energy, by incorporating a possible interaction between DM and DE. The holographic tachyon model of dark energy was also investigated in [25] and the interacting tachyon dark energy was first studied in [26]. Tachyonic fields have the attractive feature that may describe a larger variety of cosmological evolutions than quintessence fields [27]. Other relevant works on interacting and non-interacting holographic dark energy can be found in [28–32].

The rest of the paper can be outlined as follows. In Sec. II we build the interacting holographic tachyon model and plot the potential and the evolution of the tachyon field by using the latest data from observations. The conclusions are drawn in Sec. III.

II. INTERACTING HOLOGRAPHIC TACHYON DARK ENERGY MODEL

The fact that the tachyon can act as a source of dark energy with different potential forms have been widely discussed in the literature [33–36]. The tachyon can be described by an effective field theory corresponding to a tachyon condensate in a certain class of string theories with the following effective action [37, 38]

$$S=\int d^4x\sqrt{-g}\left[\frac{R}{16\pi G}-V(\phi)\sqrt{1+g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi}\right], \quad (5)$$

where $V(\phi)$ is the tachyon potential and R the Ricci scalar. The physics of tachyon condensation is described by the above action for all values of ϕ provided the string coupling and the second derivative of ϕ are small. The corresponding energy-momentum tensor of the tachyon field has the form

$$T_{\mu\nu}=\frac{V(\phi)\partial_\mu\phi\partial_\nu\phi}{\sqrt{1+g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi}}-g_{\mu\nu}V(\phi)\sqrt{1+g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi}. \quad (6)$$

In the flat FRW background the energy density ρ_t and the pressure p_t are given by

$$\rho_t=-T_0{}^0=\frac{V(\phi)}{\sqrt{1-\dot{\phi}^2}}, \quad (7)$$

$$p_t=T_i{}^i=-V(\phi)\sqrt{1-\dot{\phi}^2}, \quad (8)$$

where no summation over repeated indices is assumed and the dot stands for the derivative with respect to cosmic time.

From Eqs. (7) and (8) we obtain the tachyon equation of state parameter

$$w_t=\frac{p_t}{\rho_t}=\dot{\phi}^2-1. \quad (9)$$

In order to have a real energy density for the tachyon we require $0<\dot{\phi}^2<1$ which implies, from Eq. (9), that the equation of state parameter is constrained to $-1<w_t<0$. Hence, irrespective of the form of the potential, the tachyonic scalar field cannot achieve an equation of state parameter that enters the phantom regime.

In order to impose the holographic nature to the tachyon, we should identify $\rho_{\rm t}$ with ρ_Λ. We consider a spatially flat FRW universe filled with DM and HDE. The Friedmann equation reads

$$3M_P^2H^2=\rho_{\rm m}+\rho_{\rm t}. \quad (10)$$

Given that the matter component is mainly contributed by the cold dark matter and that it is generally assumed that baryons do not interact with the dark sector, we shall ignore the contribution of the baryon matter here for simplicity.

In the case of an interaction between HDE and DM, their energy densities no longer satisfy independent conservation laws. They obey instead

$$\dot{\rho}_m + 3H\rho_m = Q \ , \tag{11}$$

$$\dot{\rho}_t + 3H(1+\omega_t)\rho_t = -Q, \tag{12}$$

where Q is an interaction term whose form is not unique. Here in this letter we consider the following form

$$Q = 3b^2H(\rho_{\rm m} + \rho_{\rm t}), \tag{13}$$

where b^2 is the coupling constant and $3H$ is attached for dimensional consistency. This particular interaction term was first introduced on phenomenological grounds in the study of a suitable coupling between a quintessence scalar field and a pressureless cold dark matter component in order to alleviate the coincidence problem [39]. For a rationale of this particular form of the interaction term see [22].

The term b^2 gauges the intensity of the coupling, being $b^2 = 0$ the absence of interaction. Apart from this, it measures to what extent the different evolution of the DM due to its interaction with the DE gives rise to a different expansion history of the Universe. A positive b^2 corresponds to a decay of DE into DM. In fact, it can be seen that the coincidence problem is substantially alleviated in the IHDE model, unlike the ΛCDM one which does not have this advantage [15]. Furthermore, its observational signatures were recently investigated and this model was found to be mildly favored over the ΛCDM one [40].

Combining the definition of HDE (3) and that of the future event horizon (4) we take the derivative with respect to $x = \ln a$ and obtain

$$\rho'_t \equiv \frac{d\rho_t}{dx} = -6M_p^2H^2\Omega_t(1-\frac{\sqrt{\Omega_t}}{c}), \tag{14}$$

where $\Omega_t = \rho_t/(3M_p^2H^2)$. Given that, from the definition of the Hubble parameter, $\dot{\rho}_t \equiv d\rho_t/dt = \rho'_t H$ and making use of the Friedmann equation (10), Eq. (12) can be written as

$$\rho'_t + 3(1+w_t)\rho_t = -9M_p^2b^2H^2. \tag{15}$$

Combining the last two equations, we are led to the equation of state parameter of this IHDE model,

$$w_t = -\frac{1}{3} - \frac{2}{3}\frac{\sqrt{\Omega_t}}{c} - \frac{b^2}{\Omega_t}. \tag{16}$$

This is the equation we shall use throughout this letter. However, other authors [41] argued that

$$w_t^{\rm eff} = w_t + \frac{b^2}{\Omega_t} = -\frac{1}{3} - \frac{2}{3}\frac{\sqrt{\Omega_t}}{c} \tag{17}$$

should be used instead but this issue is not settled yet.

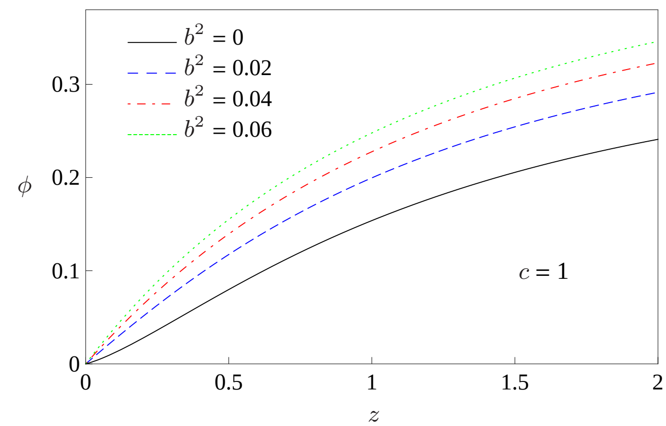

FIG. 1: The evolution of $\phi(z)$, where ϕ is in units of H_0^{-1}, for a fixed c and different values of the coupling with $\Omega_{m0} = 0.27$.

We must mention, however, that when the interaction between dark components is present, the situation may become somewhat ambiguous because the equation of state parameter w_t loses its ability to classify dark energies definitely, owing to the fact that now DE and DM are entangled. Under these conditions, concepts such as quintessence or phantom are not as clear as usual. Even though, we can still use these conceptions in an undemanding sense as the interacting term is very weak according to observations.

Inserting Eq. (16) into Eq. (15) and using the definition of Ω_t, we arrive at

$$\frac{H'}{H} = -\frac{\Omega'_t}{2\Omega_t} + \frac{\sqrt{\Omega_t}}{c} - 1. \tag{18}$$

On the other hand, replacing $\dot{H} = H'H$ and $p_t = w_t\rho_t$ into the derivative of the Friedmann equation with respect to cosmic time $\dot{H} = -\frac{1}{2M_p^2}(\rho + p)$ (where ρ and p are the total energy density and pressure respectively), we have

$$\frac{H'}{H} = \frac{1}{2}\Omega_t + \frac{\Omega_t^{3/2}}{c} + \frac{3}{2}b^2 - \frac{3}{2}. \tag{19}$$

If we combine now last two equations, we find the evolution equation for Ω_t

$$\frac{d\Omega_t}{dx} = \Omega_t(1-\Omega_t)\left(1 + \frac{2\sqrt{\Omega_t}}{c} - \frac{3b^2}{1-\Omega_t}\right), \tag{20}$$

which governs the whole dynamics of the IHDE model.

Since $\frac{d}{dt} = H\frac{d}{dx} = -H(1+z)\frac{d}{dz}$ we can rewrite the above equation with respect to z as

$$\frac{d\Omega_t}{dz} = -(1+z)^{-1}\Omega_t(1-\Omega_t)\left(1 + \frac{2\sqrt{\Omega_t}}{c} - \frac{3b^2}{1-\Omega_t}\right). \tag{21}$$

Therefore, the differential equation for the Hubble parameter $H(z)$ can be expressed as

$$\frac{dH}{dz} = -(1+z)^{-1}H\left(\frac{1}{2}\Omega_t + \frac{\Omega_t^{3/2}}{c} + \frac{3}{2}b^2 - \frac{3}{2}\right). \tag{22}$$

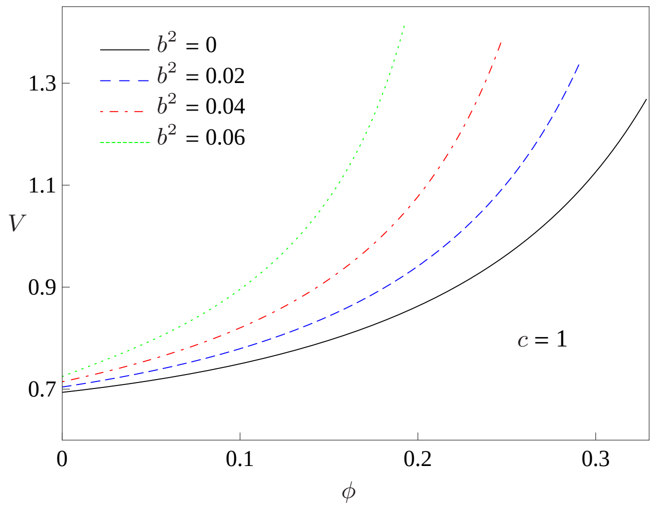

FIG. 2: The potential for the interacting holographic tachyon model, where ϕ is in units of H_0^{-1} and $V(\phi)$ in $\varrho_{cr,0}$, for a fixed c and different values of the coupling. Here we have chosen $\Omega_{m0} = 0.27$.

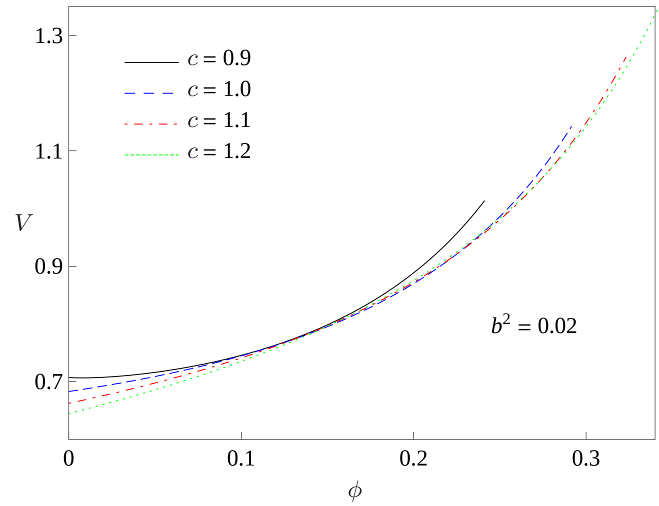

FIG. 4: The potential for the interacting holographic tachyon model, where ϕ is in units of H_0^{-1} and $V(\phi)$ in $\varrho_{cr,0}$, for a fixed coupling and different values of c with $\Omega_{m,0} = 0.27$.

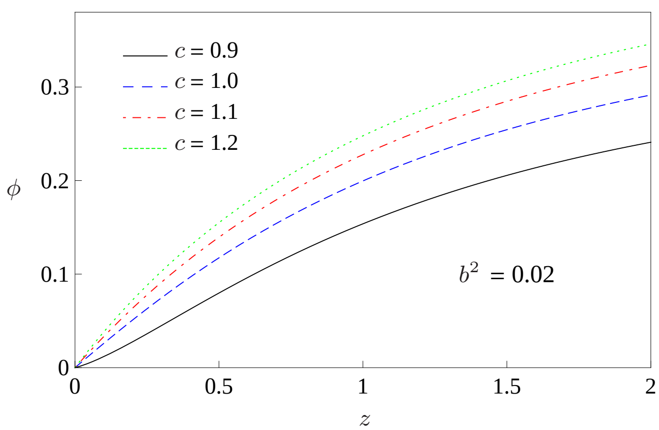

FIG. 3: The evolution of $\phi(z)$, where ϕ is in units of H_0^{-1}, for a fixed coupling and different values of c. As is usual, here we have considered $\Omega_{m,0} = 0.27$.

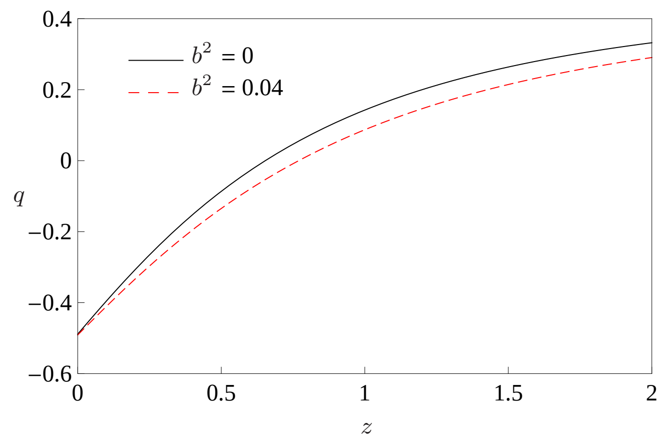

FIG. 5: Evolution of the deceleration parameter q with and without interaction for a fixed parameter $c = 1$. We take here $\Omega_{t,0} = 0.73$.

The above equations can be solved numerically to obtain the evolution of Ω_t and H as a function of the redshift.

Using Eqs. (7), (9) and (22), we derive the interacting holographic tachyon potential

$$\frac{V(\phi)}{\rho_{cr,0}} = H^2 \Omega_t \sqrt{-w_t}, \tag{23}$$

where Ω_t and w_t are respectively given by Eqs. (21) and (16), being $\rho_{cr,0} = 3M_p^2 H_0^2$ the critical energy density of the universe at the present epoch. Besides, using Eqs. (9) and (22), the derivative of the interacting holographic tachyon scalar field ϕ with respect to the redshift z can be expressed as

$$\frac{\phi'}{H_0^{-1}} = \pm \frac{\sqrt{1+w_t}}{H(1+z)}. \tag{24}$$

The sign is in fact arbitrary as it can be changed by a redefinition of the field $\phi \to -\phi$.

The above equation cannot be solved analytically, however, the evolutionary form of the interacting holographic tachyon field can be easily obtained integrating it numerically from $z = 0$ to a given value z.

The field amplitude at the present epoch ($z = 0$) is taken to vanish, $\phi(0) = 0$. Changing this initial value is equivalent to a displacement in ϕ by a constant value $\phi_0 = \phi(z = 0)$, which does not affect the shape of the field.

We note that Eqs. (23) and (24) are formally the same

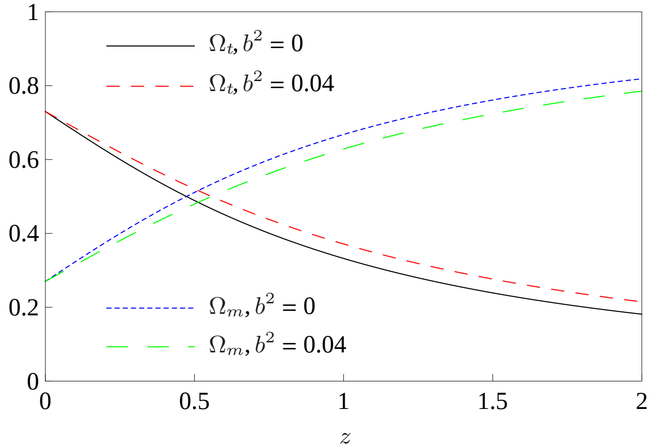

FIG. 6: Variation of Ω_t and Ω_m with respect to the redshift for the holographic tachyon model with and without interaction. We take in this plot $c = 1$ and $\Omega_{t,0} = 0.73$.

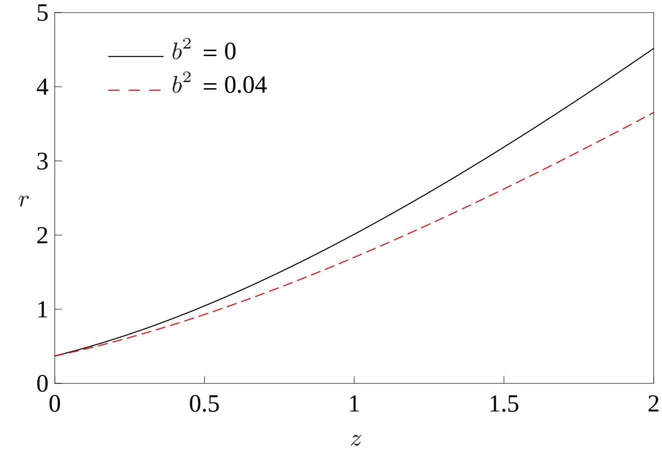

FIG. 8: Variation of the ratio $r \equiv \rho_m/\rho_t$ with respect to the redshift for the holographic tachyon model with and without interaction. We take in this plot $c = 1$ and $\Omega_{t,0} = 0.73$.

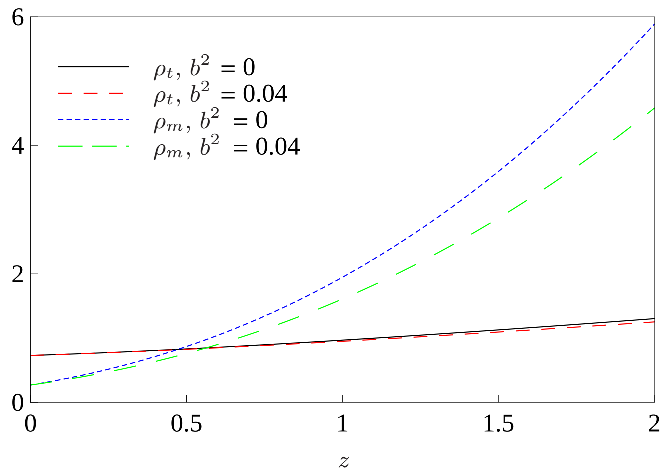

FIG. 7: Variation of ρ_t and ρ_m with respect to z in units of $\varrho_{cr,0}$ for the holographic tachyon model with and without interaction. We take in this plot $c = 1$ and $\Omega_{t,0} = 0.73$.

as in [24], but $H(z)$ is different in our case due to the interaction which modifies the expansion history of the Universe.

As already discussed in [42] the interaction Q is very weak and positive and the parameters b^2 and c are not totally free; they need to satisfy some constraints. Following the latest observational results for the IHDE models [40, 43, 44], we take $0 \leq b^2 \leq 0.06$ and $\sqrt{\Omega_t} < c < 1.255$, where the lower bound of c comes from the second law of thermodynamics. The interaction coupling has an upper limit because of the evolutionary behavior of the HDE [16]. As it can be seen in Fig. 5, where the dependence of the deceleration parameter $q = -\ddot{a}/(aH^2)$ on the coupling for a fixed c is shown, the interaction has an appreciable effect on the acceleration history of the Universe. For a fixed parameter c, the cosmic acceleration starts earlier for the cases with interaction than the one without coupling as DE dominates earlier. This result was also previously obtained by other authors [14–16, 20, 21]. Moreover, for larger coupling between DE and DM, the acceleration starts earlier. However, the cases with smaller coupling will get larger acceleration finally in the far future. Besides, the cases with a fixed small b^2 and various values of c are also interesting. The Universe starts to accelerate earlier when c is larger for the same coupling b^2, but finally a smaller c will lead to a larger acceleration [45].

The analytical form of the potential in terms of the interacting holographic tachyon field cannot be determined due to the complexity of the equations involved. Although, we can obtain it numerically. The reconstructed $V(\phi)$ is plotted in Figs. 2 and 4. The scalar field $\phi(z)$ is also reconstructed by solving Eq. (24) and shown in Figs. 1 and 3. Selected curves are plotted for the cases of $c = 1$ and $b^2 = 0, 0.02, 0.04$ and 0.06 in Figs. 1 and 2. And for the cases of $b^2 = 0.02$ and $c = 0.9, 1.0, 1.1$ and 1.2 in Figs. 3 and 4. The present fractional matter density is chosen to be $\Omega_{m,0} = 0.27$. Figs. 1 to 4 display the dynamics of the interacting tachyon scalar field explicitly. Following the interacting holographic evolution of the Universe, all the potentials are more steep in the early epoch, tending to be flat near today. Consequently, the tachyon field ϕ rolls down the potential more slowly as the Universe expands (the kinetic term $\dot{\phi}^2$ gradually decreases) and the equation of state parameter tends to negative values close to -1 according to Eq. (9) as $\dot{\phi} \to 0$. As a result $dw_t/d\ln a < 0$. Note that $\phi(z)$ increases with z but becomes finite at high redshift. This means that ϕ decreases as the Universe expands.

Similar behavior has been obtained in [24] for a holographic tachyon model. This was to be expected because the coupling that gauges the interaction in the IHDE model is small, otherwise this model would deviate significantly from the concordance model, making it incompatible with observations [46].

Fig. 6 shows the impact of the interaction between HDE and DM, namely, Ω_t increases at a faster rate as compared to the non-interacting case. In addition, from Fig. 7 we learn that the point where ρ_t and ρ_m cross, $\rho_t = \rho_m$, occurs earlier in the interacting scenario. This latter feature is appreciated in more detail in Fig. 8 where the dependence of the ratio $r \equiv \rho_m/\rho_t$ with respect to the redshift z is depicted. The aforementioned ratio decreases monotonously with the expansion and varies slowly at the present epoch, decreasing slower when the interaction is considered. This implies that in this scenario the coincidence problem gets alleviated and besides, that DE is decaying into DM in recent epochs. Furthermore, the different evolution of DM due to its interaction with DE also gives rise to a different expansion history of the Universe. Moreover, the standard structure formation scenario, with $\rho_m \propto a^{-3}$, is altered when DM interacts with DE due to a different evolution of the matter density perturbations. These matter perturbations were studied in [15, 46].

III. CONCLUSIONS

We have proposed an interacting holographic tachyon model of dark energy with the future event horizon as infrared cut-off. This has been done by establishing a correspondence between the IHDE model and the tachyon field. We have also carried out a throughout analysis of its evolution and deduce its cosmological consequences.

By assuming that the scalar field models of dark energy are effective theories of an underlying theory of dark energy and regarding the scalar field model as an effective description of such a theory, we can use the tachyon scalar field model to mimic the evolving behavior of the IHDE. As a result, we have reconstructed the interacting holographic tachyon model in the region $-1 < w < 0$, i.e. before the phantom crossing, which is the allowed region for the tachyon field.

In summary, we have shown that the interacting holographic evolution of the universe can be described completely by a tachyon scalar field and that the obtained results enter inside the valid region of different experimental data. We must finally add that a paper that deals with the interacting tachyon in the holographic context appeared recently [47] but the motivation and objectives in it are different from ours.

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