Reconstructing the interaction between dark matter and holographic dark energy

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Abstract
We reconstruct the interaction rate between dark matter and the holographic dark energy with the parametrized equation of states and the future event horizon as the infrared cutoff length. It is shown that the observational constraints from the 192 type Ia Supernovae (SnIa) and baryon acoustic oscillation (BAO) measurement permit the negative interaction in the wide region. Moreover, the usual phenomenological descriptions cannot describe the reconstructed interaction well for many cases. The other possible interaction is also discussed.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction
In the modern cosmology, ‘dark energy’ (DE) with negative pressure is suggested to be responsible for the current acceleration of the universe. The simplest candidate of DE is the cosmological constant, which does nicely well at the pragmatic observational level, but entails the serious theoretical difficulty: the cosmological constant problem and the coincidence problem. Explanations of DE have been sought within a wide range of physical phenomena, including some exotic fields, modified gravity theories, and so on (see [1] and references therein). Among the most recent generic proposals, the model inspired by the holographic idea [2] that the quantum zero-point energy of a system cannot exceed the mass of a black hole with same size has been put forward to explain the DE [3–5]. This DE density can be

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determined in terms of the horizon radius of the universe, corresponding to relate the UV cutoff of a system to its IR cutoff in the quantum field theory. There are usually three choices for the horizon radius supposed to provide the IR cutoff, with different degrees of success, namely the Hubble horizon, the particle horizon and the future event horizon. The event horizon may be better, since in this case DE can drive the present accelerated expansion, and the coincidence problem can be resolved by assuming an appropriate number of e-folding of inflation [5–7].

Most discussions on DE models rely on the fact that both dark matter (DM) and DE only couple gravitationally. However, given their unknown nature and the symmetry that would impose a vanishing interaction is still to be discovered; an entirely independent behavior between dark sectors is very special. Moreover, since DE must be accreted by massive compact objects such as black holes and neutron stars, in a cosmological context the energy transfer from DE to DM may be small but must be non-vanishing. The interaction hypothesis was first introduced by Wetterich [8] to discuss the cosmological constant problem in the light of dilatation symmetry and its anomaly. Then cosmological consequences of a scalar field coupled to the matter were studied in [9]. It was found that the coupling quintessence models may give the scaling attractors providing an accelerated expansion at the present time and alleviate the coincidence problem [10]. The interaction also appears in the context of modified gravity models [11]. More possibility that DE and DM can interact has been studied in [12–17]. Confronted to cosmological data, it was found that an appropriate interaction can influence the perturbation dynamics and the lowest multipoles of the CMB spectrum [18, 19], and could be inferred from the expansion history of the universe, as manifested in the supernova data together with the CMB and large-scale structure [20–22]. In addition, it was suggested that the dynamical equilibrium of collapsed structures would be affected by the coupling of DE to DM [23, 24]. The interaction was first connected to holography by Horvat [25] who argued that scaling of the cosmological constant stemming from the zero-point energy in quantum field theory possibly implies a non-vanishing coupling of the cosmological constant with DM. In the holographic DE model with the Hubble horizon as the IR cutoff, the interaction can be available to derive the present accelerated expansion and alleviate the coincidence problem [26]. In the interacting model with the event horizon as the IR cutoff, it was shown that the equation of state (EoS) of DE can accommodate the dynamically evolving behavior of crossing the phantom divide [27], which is suggested by recent most observational probes [28].

Although the interaction is important in studying the physics of DE, it will not be possible to derive the precise form of the interaction from first principles unless the nature of both dark sectors was known. Usually, the coupling is determined from phenomenological requirements [10, 26]. In view of the continuous equations of DE density $\rho_d$ and DM density $\rho_m$, the coupling $Q$ must be a function of densities multiplied by a quantity with units of inverse of time, which has an obvious choice as Hubble time $H^{-1}$. Thus, one may write the coupling as

$$Q = Q(H\rho_m, H\rho_d).$$

(1)

which leads $Q \simeq \lambda_m H\rho_m + \lambda_d H\rho_d$ from the first-order terms in the power law expansion. Assuming that the ratio $r = \rho_m / \rho_d$ might be piecewise constant, the linear parameters are usually set to $\lambda_m \simeq \lambda_d$ and even $\lambda_m \simeq 0$ or $\lambda_d \simeq 0$ for simplicity. Considering the couplings are terms in the Lagrangian which mix both DE and DM, one may further suppose that they could be parametrized by some product of the densities of DE and DM, such as the simplest $Q \simeq \lambda \rho_m \rho_d$ [13]. Besides these phenomenological descriptions, various proposals at the fundamental level have been tried to account for the coupling, including the dependence of the matter field on the scalar field [29] or expressing the cosmological constant as a function of the trace of the energy–momentum tensor [30]. Recently, an interesting thermodynamical
description of interaction between holographic DE and DM has been proposed in [31], where it was assumed that in the absence of the coupling DE and DM remain in separate thermal equilibrium, then a small interaction can be viewed as a stable thermal fluctuation that brings a logarithmic correction to the equilibrium entropy of DE and DM. Other specific coupling which was assumed from the outset can be found in [12, 32, 33].

The main aim of this work is to reconstruct the coupling using the recent DE probes (the baryon acoustic oscillation (BAO) measurement at \( z = 0.35 \) from the Sloan Digital Sky Survey [34] and the re-compiled 192 type Ia supernovae (SnIa) samples [35], consisting 60 points from ESSENCE (‘Equation of State: Supernovae trace Cosmic Expansion’) supernova survey [36], 57 points from Supernovae Legacy Survey [37], 45 points nearby Supernovae [38] and 30 points detected by the Hubble Space Telescope [39]). We will focus on the holographic DE model and choose the future event horizon as the IR cutoff.

The model with the Hubble horizon has been studied recently in [40], and it was found that the reconstructed interaction is always positive in 1\( \sigma \) region. This seems to corroborate the recent argument that the negative interaction violates the second law of thermodynamics which enquires the energy transfer from DE to DM rather than otherwise [41]. However, it should be noted that there are some problems in the thermodynamics of DE, such as the negative entropy [42], and the generalized thermodynamical second law indeed breaks down in the universe with phantom-dominated DE [43, 44]. These results suggest that one should consider the thermodynamical properties of DE with wide possibilities. Hence, it is interesting to see whether the positive interaction is a robust result for other models, such as the present model with the IR cutoff as the future event horizon.

Considering the time-varying DE gives a better fit than a cosmological constant and, in particular, most of the observational probes indeed mildly favor dynamical DE crossing the phantom divide at \( z \sim 0.2 \) [28], we will employ two commonly used parametrizations [21, 45–47], namely

\[
w_A = w_0 + w_1 (1 - a) = w_0 + w_1 \frac{z}{1 + z},
\]

which has been used in [40], and

\[
w_B = w_0 + w_1 (1 - a) a = w_0 + w_1 \frac{z}{(1 + z)^2}.
\]

It should be noted that the different parametrizations are beneficial to control some amount of parametrization dependence. After reconstructing the interaction, we will further compare it with the usual phenomenological models and the recent thermodynamical description.

2. Reconstruction

Let us begin with the Friedmann equations

\[
H^2 = \frac{1}{3} (\rho_m + \rho_d),
\]

\[
\dot{H} = -\frac{1}{2} (\rho_m + \rho_d + p_m + p_d),
\]

where we have normalized \( 8\pi G = 1 \) for conventions. The total energy density \( \rho = \rho_m + \rho_d \) satisfies a conservation law. However, since we consider the interaction between DE and DM, \( \rho_m \) and \( \rho_d \) do not satisfy independent conservation laws, they instead satisfy two continuous equations

\[
\dot{\rho}_m + 3H \rho_m = Q,
\]

\[
\dot{\rho}_d + 3H (1 + w_d) \rho_d = -Q.
\]
where \( w_d \) is the EoS of DE, and \( Q \) denotes the interaction term. Without loss of generality, we will write the interaction as \( Q = \rho_d \Gamma \), where \( \Gamma \) is an unknown function.

Using the ratio of energy densities \( r = \rho_m/\rho_d \), we have

\[
\frac{\dot{H}}{H^2} = -\frac{3}{2} \frac{1 + w_d + r}{1 + r}
\]  
(8)

from equation (5). From equation (6), we have

\[
\dot{r} = -\frac{\dot{\rho}_d}{\rho_d} - 3Hr + \Gamma,
\]

which can be recast as

\[
\dot{r} = (1 + r)\Gamma + 3Hr w_d
\]  
(9)

from equation (7). Eliminating \( \Gamma \) in the above two equations, we obtain

\[
-\frac{r\dot{r} - 3Hrw_d}{1 + r} = \frac{\dot{\rho}_d}{\rho_d} + 3Hr.
\]  
(10)

Until now, we have not specified the concrete DE density. We will focus on the holographic DE model. Following [5] by choosing the future event horizon,

\[
R_E = a \int_a^\infty \frac{dx}{Hx^2},
\]  
(11)

as the IR cutoff, the holographic DE density is \( \rho_d = 3c^2R_E^{-2} \), where \( c^2 \) is a constant and the Planck mass has been considered as unit. The most possible theoretical value of \( c \) is one [5, 6], indicating that the total energy from DE must be determined by the Schwarzschild relation. Taking the derivative with respect to \( t \), the evolution of the horizon can be determined by

\[
\dot{R}_E = H R_E - 1.
\]

Defining \( \Omega_d = \rho_d/3H^2 \), we have \( \Omega_d = 1/(1 + r) \) and \( R_E = c\sqrt{1 + r}/H \). Thus, equation (10) can be recast as

\[
-\frac{r\dot{r} - 3Hrw_d}{1 + r} = r - \frac{2H(c\sqrt{1 + r} - 1)}{c\sqrt{1 + r}} + 3Hr.
\]  
(12)

Obviously, \( r \) is not a constant in general. This is different with the case in [40] where \( r \) is a constant since the IR cutoff was chosen as the Hubble scale. Replacing the time \( t \) as the redshift \( z = (1 - a)/a \), we can rewrite equation (12) as

\[
\frac{-(1 + z)r'r' + 3r w_d}{1 + r} = r \frac{2(c\sqrt{1 + r} - 1)}{c\sqrt{1 + r}} - 3r,
\]  
(13)

where the prime denotes the derivative with respect to \( z \). Similarly, equation (8) reads

\[
\frac{H'}{H} = \frac{3}{2(1 + z)} \frac{1 + w_d + r}{1 + r}.
\]  
(14)

It is interesting to find that equations (13) and (14) determine the evolvement of \( r \) and \( H \), if we know the EoS \( w_d \). In the normal interacting DE model, one assumes the explicit interaction form to give out \( w_d \). For our aim, we will use the two commonly used parametrizations of \( w_d \) to determine the dynamics of our model, and reconstruct the interaction rate \( \Gamma/3H \):

\[
\frac{\Gamma}{3H} = -(1 + z)r' + 3r w_d
\]  
from the recent observational data sets.
Table 1. The best-fit values with 1σ error bars for the parameters of $w_d$ with the DM density parameter $\Omega_0 = 0.25$.

| $c$ | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 |
|-----|-----|-----|-----|-----|-----|
| $w_A$ | $w_0$ | $-1.19 \pm 0.18$ | $-1.16 \pm 0.16$ | $-1.14 \pm 0.16$ | $-1.13 \pm 0.15$ | $-1.12 \pm 0.14$ |
| | $w_1$ | $0.60 \pm 1.26$ | $1.09 \pm 1.07$ | $1.35 \pm 0.97$ | $1.50 \pm 0.90$ | $1.60 \pm 0.85$ |
| $w_B$ | $w_0$ | $-1.21 \pm 0.24$ | $-1.21 \pm 0.22$ | $-1.21 \pm 0.20$ | $-1.21 \pm 0.19$ | $-1.20 \pm 0.19$ |
| | $w_1$ | $0.99 \pm 2.11$ | $1.83 \pm 1.83$ | $2.29 \pm 1.66$ | $2.58 \pm 1.55$ | $2.78 \pm 1.47$ |

Table 2. The best-fit values with 1σ error bars for the parameters of $w_d$ with the DM density parameter $\Omega_0 = 0.3$.

| $c$ | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 |
|-----|-----|-----|-----|-----|-----|
| $w_A$ | $w_0$ | $-1.03 \pm 0.20$ | $-1.03 \pm 0.18$ | $-1.03 \pm 0.16$ | $-1.03 \pm 0.16$ | $-1.02 \pm 0.15$ |
| | $w_1$ | $0.48 \pm 1.28$ | $0.48 \pm 1.09$ | $0.48 \pm 0.98$ | $0.70 \pm 0.92$ | $0.85 \pm 0.87$ |
| $w_B$ | $w_0$ | $-0.99 \pm 0.26$ | $-1.02 \pm 0.23$ | $-1.04 \pm 0.22$ | $-1.05 \pm 0.21$ | $-1.05 \pm 0.20$ |
| | $w_1$ | $-1.14 \pm 2.20$ | $0.03 \pm 1.90$ | $0.68 \pm 1.73$ | $1.09 \pm 1.62$ | $1.37 \pm 1.54$ |

We will use the re-compiled 192 SnIa samples ($0 < z < 1.8$) combined with the recent BAO measurement from SDSS to reconstruct the interaction rate. There are other DE observational probes, including the three-year WMAP CMB shift parameter, the x-ray gas mass fraction in clusters, the linear growth rate of perturbations at $z = 0.15$ as obtained from the 2 dF galaxy redshift survey and the look back age data. However, since the parametrizations of $w_d$ (2) and (3) are motivated to accommodate the dynamically evolving behavior of crossing the phantom divide at recent epoch, and our model has not included the radiation and the baryonic matter which may be important in the early, we will not use the WMAP CMB shift parameter which focuses on the high redshift region. Besides, for simplicity, we do not adopt other probes of DE which have large relative errors compared with SnIa, CMB and BAO probes [48].

As usual, we will fix the DM density parameter as $\Omega_0 = 0.3$ or 0.25 to include the best-fit value of $\Omega_0 = 0.27$ from five-year WMAP data. In general, they are sufficiently representative. Moreover, it is convenient to compare our reconstructed interaction to the interaction reconstructed in [40] where these two DM density parameters are used. We will consider five indicative different values of the constant $c$ near one. The best-fit values with 1σ error bars for the parameters $w_0$ and $w_1$ are given in tables 1 and 2. One can find that the phantom divide crossing in recent epoch is always permitted in 1σ region. The deceleration parameter with these best-fit equation of states is plotted in figure 1, where the acceleration (super-acceleration, at most cases) in recent epoch is achieved. It is interesting to see that the current deceleration parameter in the interacting model is almost not affected by the DE parameter $c$, according to the almost same parameters $w_0$ in tables 1 and 2. We also show the evolution of $\rho_m$ compared to its non-interacting version $\rho_m^0$ in figure 2. The ratios change strongly in recent epoch which implies the interaction plays an important role in that time. The corresponding plots for the DE component are given in figure 3. Since the DE density is always positive, this suggests that the interaction can be negative but cannot be too negative when $w_d > -1$, which is possible at least in the past.

With these best-fit values, we reconstruct the interaction rates; see figures 4 and 5. This is one of the main results of this paper. It should be stressed that the negative interaction
is permitted in the wide region of figures 4 and 5. This is in contrast to the result in [40] where the reconstructed interaction is always positive, and the argument that the second law of thermodynamics which imposes energy transfer from DE to DM [41]. If the second law is true, then the permitted region of the interaction rates must be reduced, as done in [49]. However, for generality and considering the thermodynamical properties of DE are not clear, we will not restrict the interaction to be positive.

Moreover, the effective EoS, $w_{\text{eff}} = w_d + \frac{\Gamma}{3H}$, can be obtained since we have known $w_d$ and reconstructed $\Gamma/3H$. From tables 1 and 2 and figures 4, 5, one can know that the effective EoS may be bigger or smaller than $-1$ for different parameters $\Omega_{0m}$ and $c$. If one requires effective phantom-like DE, the presence of a coupling makes the parameters have
negative. This suggests that the negative interaction is interesting because DE with $w_d < -1$ more possible values than the case of the absence of a coupling, where the EoS is determined by $w_d = -\frac{1}{3} - \frac{1}{3} \sqrt{2} \Omega_m$ which imposes $c < \sqrt{2} \Omega_m$ for $w_d < -1$. Moreover, it is possible to have effective EoS $w_{\text{eff}}$ smaller than $-1$ but $w_d$ bigger than $-1$ when the interaction is negative. This suggests that the negative interaction is interesting because DE with $w_d > -1$. 

Figure 4. Interaction rates for $\Omega_m = 0.3$ with respect to redshift $z$. Above and below panels denote $w_d = w_4$ and $w_B$, respectively. The black curves and the gray region between them indicate the best-fit curve of the reconstructed interaction rate $\Gamma/3H$ and the region in the 1$\sigma$ confidence level. The black dashing lines indicate $\Gamma/3H = 0$. The red, green, blue and yellow curves indicate $R_i$ from $i = 1$ to $i = 4$ with four constants $\lambda$. For example, we give $\lambda = 0.13, 0.11, 0.07, 0.2$ in turn for $w_d = w_4$ and $c = 1$. The blue dashing lines indicate the interaction rate $R_5$. The red dashing lines in the case with $c = 0.6$ indicate the interaction rate $R_6$ with two nonzero constants. For the above panel, they are $\lambda_1 = 0.17, \lambda_2 = -0.16$. For the below panel, they are $\lambda_1 = 0.11, \lambda_2 = -0.15$.

Figure 5. Interaction rates for $\Omega_m = 0.25$. The blue dashing lines indicate the interaction rate $R_5$. The red dashing lines indicate the interaction rate $R_6$ with some constants $\lambda_i$ ($i = 1, \ldots, 5$).
is easily accepted (the scalar field with $w_d < -1$ will break the zero-energy condition.) and the effective EoS of DE $w_{eff} < -1$ can fit the cosmological data better.

3. Comparison

In the following, we will compare the reconstructed interaction rate with other descriptions. Let us begin with the usual phenomenological descriptions. Usually there are four different choices of $Q_i$ ($i = 1, 2, 3, 4$), which can be expressed as $\lambda \rho_d$, $\lambda \rho_m$, $\lambda (\rho_m + \rho_d)$ and $\lambda \rho_m \rho_d$, respectively. To compare them with the reconstructed interaction rate $\Gamma / \sqrt{\Omega_d}$, we define four interaction rates $R_i = Q_i / (\lambda \rho_d)$, which can be determined by $r$ and $H$ (which have been solved from equations (13) and (14)), namely $R_1 = \lambda$, $R_2 = \lambda r$, $R_3 = \lambda (1 + r)$ and $R_4 = \lambda H r / (1 + r)$. Observing figure 4, the indicative curves of the usual interaction rates $R_i$ ($i = 1, 2, 3, 4$) show that in many cases they are not favored in $1\sigma$ region. For example, see the case of $c = 1.2$, where the interaction rates $R_2$ (green line) and $R_3$ (blue line) are permitted in $1\sigma$ region, but the other interaction rates $R_1$ (red line) and $R_2$ (yellow line) are not permitted whether $\lambda$ increases or decreases. For the case $c = 0.6$, the reconstructed interaction rate changes at recent epoch from positive to negative. This tendency is more general in figure 5 with the small DM parameter $\Omega_0 = 0.25$. Thus, one may suspect that the four phenomenological descriptions of the interaction which have the definitive sign may not be suitable.

We will also consider the recent thermodynamical description of the interaction. Defining $Q_5 = 3 \lambda \rho_d$, the thermodynamical interaction rate $b^2$ can be determined by the following equations (see [31] in detail):

\[
b^2 = \frac{2 \Omega_0^{3/2}}{3c} \left[ 1 + \frac{H^2 \sqrt{\Omega_d}}{(H^0)^2 \sqrt{\Omega_d/c - 1}} \sqrt{\Omega_d/c} - 1 \right] + \frac{1}{12 \pi c^2 c/\sqrt{\Omega_d/c - 1}} \frac{H^2}{\sqrt{\Omega_d/c}} (\Omega_d - 1) \sqrt{\Omega_d/c} (1 + z),
\]

\[- (1 + z) \frac{\Omega_d'}{\Omega_d} + (\Omega_d - 1) + \frac{2 \sqrt{\Omega_d}}{c} (\Omega_d - 1) = -3 b^2,
\]

\[- (1 + z) H^2 = \frac{\sqrt{\Omega_d}}{c} - 1 + \frac{(1 + z) \Omega_d'}{2\Omega_d},
\]

where the zero superscript of $\Omega_d$ and $H^0$ indicates the absence of interaction. We can relate $b^2$ to a new interaction rate

\[R_5 = \frac{Q_5}{3 \rho_d} = \frac{b^2 (\rho_m + \rho_d)}{\rho_d} = \frac{b^2}{\Omega_d}.
\]

In figures 4 and 5 (blue dashing lines), one can find that $R_5$ is almost not favored in $1\sigma$ region (note, we have not shown the cases with $c < 1$ where $b^2$ is not the real solution and the parameterization of $w_d$ is not needed to determine $R_5$ since the EoS in this model is determined by $b^2$).

It is interesting to ask whether the reconstructed interaction can be described well by a more general interaction form. A natural candidate is to expand the phenomenological description (1) up to the second order, namely

\[Q_6 = 3 \lambda_1 H \rho_m + 3 \lambda_2 H \rho_d + \lambda_3 H^2 \rho_m \rho_d + \lambda_4 H^2 \rho_m^2 + \lambda_5 H^2 \rho_d^2.
\]
with the interaction rate

\[ R_6 = \frac{Q_6}{3H\rho_d} = \lambda_1 r + \lambda_2 + \lambda_3 \frac{H^3 r}{1 + r} + \lambda_4 \frac{H^3 r^2}{1 + r} + \lambda_5 \frac{H^3}{1 + r}. \]

We find that it indeed works well; see the red dashed line in figures 4 and 5. However, this parametrization only has theoretical interest since it contains too many parameters. Moreover, numerical calculations prove that this parametrization cannot be reduced to include only the two first-order terms, which has been studied recently in [49], if we need it being permitted in 1\(\sigma\) region for all cases.

4. Summary

We have reconstructed the interaction term between the holographic DE and DM, using the recompiled 192 SnIa samples combined with the recent BAO measurement. The DE parameter \(c\) is assumed near one. The two common used parametrizations of \(w_d\) are considered in 1\(\sigma\) region. It is found that the present accelerated expansion of the universe is achieved and the phantom behavior of DE is permitted. We illustrate that the negative interaction is permitted in the wide region. Hence, in contrast to the DE model studied in [40], where the reconstructed interaction is always positive in 1\(\sigma\) region, we cannot obtain the favor from the DM observation for the recent argued thermodynamical second law which imposes the energy transfer from DE to DM. This suggests to keep wide possibilities of the thermodynamical properties of DE.

We show that the four usual phenomenological descriptions cannot describe the reconstructed interaction well for many cases. Specially, for the case with the small DM parameter \(\Omega_{1m} = 0.25\), the interaction rate has a trend to change sign at recent epoch. This is at variance with the usual phenomenological interacting terms which have the definitive sign. We further illustrate that the recent thermodynamical description of the interaction is not favored. Our work stimulates one to seek a more suitable interaction.

It would be interesting to confront our model with more observations, such as CMB angular power and large scale structure, which will further constrain the interaction rate and make clear if the negative interaction and phantom DE are still to be permitted. Another interesting work is to consider the perturbation evolution in our model. Recently, it has been found that some types of interaction will lead to instability under the curvature perturbation [50, 51]. It may provide some restrictions on the form of interaction. We will work on these directions in the future.

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