The particle versus the future event horizon in an interacting holographic dark energy model

H Mohseni Sadjadi
Department of Physics, University of Tehran, POB 14395-547, Tehran 14399-55961, Iran
E-mail: mohseni@phymail.ut.ac.ir and mohsenisad@ut.ac.ir

Received 14 January 2007
Accepted 6 February 2007
Published 23 February 2007

Online at stacks.iop.org/JCAP/2007/i=02/a=026
doi:10.1088/1475-7516/2007/02/026

Abstract. Choosing the future event horizon as the horizon of the flat Friedmann–Lemaitre–Robertson–Walker universe, we show that the interacting holographic dark energy model is able to explain the phantom divide line crossing. We show that if we take the particle event horizon as the horizon of the universe, besides describing the $\omega = -1$ crossing (based on astrophysical data), we are able to determine appropriately the ratio of dark matter to dark energy density at the transition time. In this approach, after the first transition from the quintessence to the phantom phase, there is another transition from the phantom to the quintessence phase which avoids the big rip singularity.

Keywords: dark energy theory, inflation
1. Introduction

On the basis of astrophysical data, it is believed that the expansion of the universe is accelerating [1]. To explain the present inflation one may assume that 70% of the universe is composed of a form of energy, dubbed dark energy [2], that permeates all of space and has negative pressure. Many dark energy candidates such as the cosmological constant, $\Lambda$ (vacuum energy density) [3], dynamical exotic scalar fields with negative pressure [4] and so on have been introduced in the literature. In the cosmological constant model, the dark energy density, $\rho_\Lambda$, remains constant throughout the entire history of the universe, while the matter density decreases during the expansion. So, in this model there must be a rapid transition from a matter dominated to a dark energy dominated era. This is in contrast with the astrophysical observations which show that dark energy and matter densities are of the same order of magnitude in the present epoch. This is known as the coincidence problem [5], which also arises in dark energy models consisting of non-interacting exotic fields. By considering an appropriate interaction between dark matter and dark energy components which converts dark energy into matter, one may be able to cure this problem [6]. In [7], in some detail, it was discussed how the vacuum energy density couples to the matter fields through matter creation pressure. The process couples cosmic vacuum (dark) energy to matter to produce future-directed increasingly comparable amplitudes in these fields.

Some present data seem to favour an evolving dark energy, with an equation of state parameter (EOS), $\omega_d$, less than $-1$ (the phantom phase) at the present epoch evolving from $\omega_d > -1$ (the quintessence phase) in the recent past [8]. So it may be interesting to take into account the possibility that the universe exhibits phantom-like behaviour in the present epoch or in the future. $\omega = -1$ crossing is not allowed in minimally coupled dark energy models [9], but in multifield models, models with non-minimal coupling between scalar field and gravity, and in the framework of the scalar–tensor theory of gravity this transition is admissible [10]. A question which may arise is that of why $\omega_d = -1$ crossing has been occurring in the present epoch. This can be regarded as the second cosmological coincidence problem [11]. Crossing the phantom divide line (i.e., crossing $\omega = -1$) may also give rise to a big rip singularity [12] in a finite future time.

On the basis of holographic ideas [13, 14], one can determine the dark energy density in terms of the horizon radius of the universe. Following [15], one can show that choosing the particle horizon as the infrared cut-off in the holographic dark energy model leads to
a decelerating universe. In [14], the future event horizon was examined and it was shown that this choice leads to the expected acceleration of the universe.

To study the acceleration of the universe and the cosmological coincidence without considering energy exchange between dark matter and dark energy, a different approach was proposed in [16], assuming that the energy density is proportional to the inverse of the area of the particle horizon within a closed universe. Depending on the constant of proportionality, either the ensuing inflationary period prevents the particle horizon from vanishing, or it may lead to a sequence of big rips as the particle horizon repeatedly traverses the closed universe. This model does not require the decay of matter, and has a natural reference scale, the radius of curvature.

In this paper we consider the interacting holographic dark energy model, i.e. we assume that the amount of dark energy is proportional to the mass of a black hole with the same radius as the event horizon of the universe [14], and besides, we assume that there is an interaction between dark matter and dark energy (the (interacting) holographic dark energy model was discussed in depth in the literature [17]). We show that by appropriately choosing the parameters of interaction between dark energy and cold dark matter, one can explain \( \omega = -1 \) crossing in a flat Friedmann–Lemaître–Robertson–Walker (FLRW) universe. In this paper, \( \omega \) denotes the EOS parameter of the universe. In the first part, the future event horizon is taken as the horizon. We show that this choice, although it can describe the phantom divide line crossing of the universe, is inconsistent with the thermodynamic second law for the horizon (the thermodynamics of the expanding universe has been the subject of several studies [18]). In addition, after the transition, the universe remains in the phantom phase and there is the possibility of encountering the big rip singularity.

Subsequently, we show that if we take the particle event horizon as the horizon of the universe, besides describing the \( \omega = -1 \) crossing, by choosing suitable interaction parameters (based on astrophysical data), we are able to determine appropriately the ratio of dark matter to dark energy density at the transition time. In this approach, after the first transition from the quintessence to the phantom phase, there is another transition from the phantom to the quintessence phase which avoids the big rip singularity.

We use units \( \hbar = c = G = k_B = 1 \) throughout the paper.

2. Preliminaries

We consider the flat FLRW metric and assume that the universe is composed of two perfect fluids, cold (pressureless) dark matter and dark energy. We consider exchange of energy between these components, so they do not evolve independently:

\[
\begin{align*}
\dot{\rho}_m + 3H\rho_m &= Q \\
\dot{\rho}_d + 3H(1 + \omega_d)\rho_d &= -Q.
\end{align*}
\] (1)

\( H \) is the Hubble parameter which in terms of the scale factor \( a(t) \) can be written as \( H = \dot{a}(t)/a(t) \). The overdot indicates the derivative with respect to the comoving time. \( \rho_m \) and \( \rho_d \) are dark matter and dark energy densities respectively. \( \omega_d \) is the equation of state parameter of dark energy. \( Q \) is the interaction term which may be taken as [6]

\[
Q = (\lambda_m\rho_m + \lambda_d\rho_d)H.
\] (2)
\( \lambda_m \) and \( \lambda_d \) are two numerical constants. Whereas dark matter and dark energy stress-energy tensors are not conserved, the total stress-energy tensor is conserved:

\[
\dot{\rho} + 3H(1 + \omega)\rho = 0. \tag{3}
\]

\( \rho = \rho_m + \rho_d \) is the total fluid density of the universe, in terms of which we have

\[
\dot{H} = -4\pi(1 + \omega)\rho. \tag{4}
\]

The EOS of dark energy component can be written as

\[
\omega_d = \omega_{\Omega_d}, \tag{5}
\]

where \( \Omega_d \) denotes the ratio of dark energy density, \( \rho_d \), to the total density \( \rho \): \( \Omega_d = \rho_d/\rho \). Note that \( 0 < \Omega_d < 1 \), and therefore for \( \omega \leq -1 \), we have always \( \omega_d < -1 \), i.e. if the quintessence to phantom phase transition occurs, the dark energy component must exhibit phantom-like behaviour but the inverse is not true: the dark energy component may be phantom-like: \( \omega_d < -1 \), while the universe remains in the quintessence phase, \(-1 < \omega < -1/3 \).

Using equations (1), (2) and (4), one can verify that the evolution equation of the ratio of densities of dark matter and dark energy, denoted by \( r = \rho_m/\rho_d \), satisfies

\[
\dot{r} = r(r + 1)H \left( 3\omega + \frac{\lambda_m}{r} \right). \tag{6}
\]

Using

\[
\Omega_d := \frac{\rho_d}{\rho} = \frac{1}{1 + r}, \tag{7}
\]

we find

\[
\omega = \frac{1}{3H} \frac{\dot{\Omega}_d}{(1 - \Omega_d)} - \frac{\lambda_d \Omega_d}{3(1 - \Omega_d)} - \frac{\lambda_m}{3}. \tag{8}
\]

One can consider \( \rho_d \) as the holographic dark energy density [14]

\[
\rho_d = \frac{3}{8\pi} \frac{c^2}{L^2}, \tag{9}
\]

where \( c \) is a positive numerical constant and \( L \) is the infrared cut-off. A cut-off candidate is the future event horizon defined by

\[
R_f = a(t) \int_t^{\infty} \frac{1}{a(t')} \, dt'. \tag{10}
\]

In the presence of big rip at \( t = t_s \), \( \infty \) in (10) must be replaced with \( t_s \). Using

\[
\dot{R}_f = HR_f - 1, \tag{11}
\]

which follows from (10), and \( HR_f = c/\sqrt{\Omega_d} \), we arrive at

\[
\omega = -\frac{1}{3} - \frac{2}{3} \frac{\sqrt{\Omega_d}}{c} + \frac{1}{3H} \frac{\dot{\Omega}_d}{\Omega_d}. \tag{12}
\]
To derive (12) we have also used \( \omega = -1 - 2\dot{H}/(3H^2) \). Equations (8) and (12) may be used to determine \( \omega \) and \( \dot{\Omega}_d \) in terms of \( \Omega_d \):

\[
\omega = -\frac{1 + \lambda_d - \lambda_m}{3} \Omega_d - \frac{2}{3c} \Omega_d^{3/2} - \frac{\lambda_m}{3},
\]

(13)

\[
\dot{\Omega}_d = H \Omega_d \left( 3\omega + 1 + \frac{2}{c} \sqrt{\Omega_d} \right).
\]

(14)

Note that, by definition, \( \Omega_d \) lies in \((0, 1)\). If at a specific point, \( \dot{\Omega}_d = 0 \), (14) implies that higher derivatives of \( \Omega_d \) must also be zero at that point (denoted as the point of infinite flatness). Considering that \( \Omega_d \) is an analytic function, infinite flatness may only occur at \( t \to \infty \).

3. Future event horizon and \( \omega = -1 \) crossing

In the quintessence phase we have \(-1 < \omega < -1/3\), while in the phantom phase \( \omega < -1 \). At the transition time, we have \( \omega = -1 \). So if the transition is allowed then \( \omega(\Omega_d) + 1 \) has at least one positive root in \((0, 1)\) and \( \omega \) is a decreasing function of time in the neighbourhood of this root. In terms of \( u \) defined by \( u = \sqrt{\Omega_d} \), \( \omega = -1 \) becomes

\[
u^3 + pu^2 + q = 0,
\]

(15)

where

\[
p = \frac{c}{2}(1 + \lambda_d - \lambda_m), \quad q = \frac{c}{2}(\lambda_m - 3).
\]

(16)

In order to have a quintessence to phantom phase transition, the cubic equation (15) must have at least one root in \((0, 1)\). In addition, at the transition time we must have \( \dot{\omega} \leq 0 \).

\[
\dot{\omega} = -\dot{\Omega}_d \left( \frac{2p}{3c} + \frac{\sqrt{\Omega_d}}{c} \right),
\]

(17)

leads to

\[
\dot{\omega} = -2Hu^2 \left( \frac{u}{c} - 1 \right) \left( \frac{2p}{3c} + \frac{u}{c} \right),
\]

(18)

at \( \omega = -1 \). Therefore \( \dot{\omega} < 0 \), at the transition time, is satisfied when

\[
0 < u < \text{Minimum} \left\{ c, -\frac{2p}{3} \right\},
\]

(19)

or

\[
\text{Maximum} \left\{ c, -\frac{2p}{3} \right\} < u < 1.
\]

(20)

To go further let us discuss the behaviour of the future event horizon at transition time, denoted by \( t = t_0 \). In the neighbourhood of \( t_0 \), we have \( H(t) = H(t_0) + h_\alpha(t - t_0)^\alpha \), where \( h_\alpha = (1/\alpha!)H^{(\alpha)}(t_0) \), and \( \alpha \) is the order of the first non-zero derivative of \( H \) at \( t_0 \): \( H^{(\alpha)} = d^\alpha H/dt^\alpha > 0 \). Note that \( \alpha \) is an even positive integer and \( h_\alpha \) is positive [21]. In
a universe which will remain in the phantom phase, the future event horizon is a non-increasing function of time: \( \dot{R}_t \leq 0 \) [22]. Using (11), we obtain the following expansions for \( R_t \):

\[
R_t(t) = R_t(t_0) \left(1 + \frac{h_0}{\alpha + 1} (t - t_0)^{\alpha + 1}\right),
\]

provided that \( \dot{R}_t(t_0) = 0 \), and

\[
R_t(t) = R_t(t_0) + (R_t(t_0)H(t_0) - 1) (t - t_0),
\]

when \( \dot{R}_t(t_0) \neq 0 \). In the case (21), we have \( \dot{R}_t(t) = R_t(t_0) h_0 (t - t_0)^\alpha \), and therefore for \( t > t_0 \), \( \dot{R}_t(t) > 0 \) which is conflict with the fact that in the phantom era the future event horizon is non-increasing. Hence at the quintessence to phantom transition time we must have \( \dot{R}_t \neq 0 \) which, considering \( \dot{R}_t(t > t_0) \leq 0 \), leads to \( \dot{R}_t(t = t_0) = H(t_0) R_t(t_0) - 1 < 0 \), and therefore using the continuity of \( R_t \) we conclude that there exists a neighbourhood, \( N \) of \( t_0 \), for which \( \dot{R}_t(t \in N) < 0 \).

It should be noted that the validity of the above results is contingent on the fact that the universe will remain in the phantom phase for all future times, i.e. if there is another transition from a phantom to a quintessence phase, we may have \( \dot{R}_t > 0 \), even in a phantom era. If this situation is allowed, (15) must have two roots in \((0, 1)\). Therefore Rolle’s theorem implies that there exists a \( t \in (0, 1) \) such that \( \dot{\omega}(t) = 0 \). At this time we have \( u = -2p/3 \) and \( \dot{\omega} = -\Omega^2_\Lambda / (2c\sqrt{\Omega_\Lambda}) < 0 \) which follows from (13). Therefore \( \omega \) is a concave function and the (possibly) allowed successive transitions are phantom \( \rightarrow \) quintessence \( \rightarrow \) phantom. Hence we conclude that even in the presence of two transitions, after the quintessence to phantom transition the system remains in the phantom phase and the thermodynamics second law fails. On the other hand, considering \( HR_t = c/u \), \( \dot{R}_t \geq 0 \) is satisfied when and only when \( u \leq c \) (see (11)), and therefore following the above discussion which implies that at transition time \( \dot{R}_F < 0 \), only the choice (20) is allowed. Equation (20) also implies that there is a lower bound for dark energy density at the transition time.

As an example let us assume Maximum\( \{c, -2p/3\} = -2p/3 \). In this case, at the transition time we must have \(-2p/3 < u < 1\). In order for the transition to occur the cubic polynomial \( Q(u) := u^3 + p u^2 + q \) must have at least a positive root in \((-2p/3, 1)\). Following the Descartes sign rule, for \( p \geq 0, q < 0 \) and \( p < 0, q \leq 0 \), \( Q(u) \) has a positive root, while for \( p < 0, q > 0 \) it has either two or no positive roots. Consider the sequence \( D = \{u^3 + pu^2 + q, 3u^2 + 2pu, 6u + 2p, 6\} \). We have

\[
D(1) = \{1 + p + q, 3 + 2p, 6 + 2p, 6\}
\]

\[
D \left( -\frac{2p}{3} \right) = \left\{ \frac{4p^3}{27} + q, 0, -2p, 6 \right\}.
\]

By applying the Budan–Fourier theorem and the Descartes sign rule (and considering \( 0 < -2p < 3 \) which results in \( 1 + p > 4p^3/27 \)), we conclude that \( Q \) at most has one root in \((-2p/3, 1)\), provided

\[
\frac{4p^3}{27} + q < 0, \quad 1 + p + q \geq 0.
\]
As an illustration, the plot of $\omega$ is depicted for $(p = -1/3, q = -1/2, c = 1/6)$ corresponding to $(\lambda_m = -3, \lambda_d = -8, c = 1/6)$ and $(p = -1, q = 1/9, c = 1/3)$ corresponding to $(\lambda_m = 11/3, \lambda_d = -10/3$ and $c = 1/3)$ in figure 1. For $(p = -1/3, q = -1/2, c = 1/6)$, $q$ is negative and $\omega = -1$ has only one root which lies in $(-2p/3, 1)$. In this case the transition is quintessence $\rightarrow$ phantom. For $(p = -1, q = 1/9, c = 1/3)$, $q$ is positive and $\omega = -1$ has two roots in $(0, 1)$. One of these roots lies in $(-2p/3, 1)$.

Note that in this case, as we have verified previously, the transitions are phantom $\rightarrow$ quintessence $\rightarrow$ phantom.

At the end of this section it is worth noting that if we assign an entropy to the future event horizon via

$$S = \pi R_f^2,$$  \hspace{1cm} (25)

our previous discussions reveal that the second thermodynamic law for the horizon is not respected at least in the transition epoch: $\dot{S}(t \simeq t_0) < 0$. Note that $\dot{S}(t > t_0) \leq 0$ in the phantom phase. The above entropy may be assumed as the entropy of the whole system [14,19]; indeed in the holographic approach, all information stored within some volume is represented on the boundary of that region.

From another point of view the entropy attributed to the horizon is considered as a measure of our ignorance about what is going on behind it. In this approach the total entropy of the universe, $S_T$, is the sum of the entropy of perfect fluids inside the horizon, $S_m$, and the horizon entropy, $S_T = S + S_m$. In this way the validity of the generalized second law (GSL) of thermodynamics, i.e. $\dot{S}_T \geq 0$, may be investigated [20]. Recently in [21] it has been shown that, at least at the transition epoch, the GSL is not respected.

In brief, in this section we have shown that although we take the future event horizon as the infrared cut-off, the holographic dark energy model can describe the $\omega = -1$
crossing. Besides, in this model, the universe will remain in the phantom phase after the transition(s) and the cosmological evolution may be ended by a big rip singularity.

4. Particle horizon and twice crossing \( \omega = -1 \)

In this section we consider the particle horizon defined by

\[
R_p = a \int_0^{t} \frac{dt'}{a(t')} ,
\]

(26)
as the infrared cut-off and study \( \omega = -1 \) crossing in an accelerated expanding universe. In this situation, (13) and (14) must be replaced with

\[
\omega = - \frac{1 + \lambda_d - \lambda_m}{3} \Omega_d + \frac{2}{3c} \Omega_d^{3/2} - \frac{\lambda_m}{3}
\]

(27)

and

\[
\dot{\Omega}_d = H \Omega_d \left( 3\omega + 1 - \frac{2}{c} \sqrt{\Omega_d} \right) ,
\]

(28)

respectively. For \( \omega < -1/3 \), i.e. for an accelerated expanding universe, \( \Omega_d \) is a decreasing function of comoving time. In terms of \( p \) and \( q \) defined in (16), we have

\[
\omega + 1 = \frac{2}{3c} (u^3 - pu^2 - q) .
\]

(29)

Following the Descartes sign rule, the equation \( \omega + 1 \) may have two positive real roots only when \( p > 0, q < 0 \). If the equation \( \omega + 1 = 0 \) has two roots in \((0, 1)\), following Rolle’s theorem we expect that \( \dot{\omega}(t) = 0 \) for a \( t \) between the roots. \( \dot{\omega} = 0 \) occurs at \( u = 2p/3 \), and at this point \( \ddot{\omega} = \Omega_d^2/(2c \sqrt{\Omega_d}) > 0 \), which shows that \( \omega(t) \) is a convex function. At \( \omega = -1 \),

\[
\ddot{\omega} = 2Hu^2 \left( -1 - \frac{u}{c} \right) \left( -\frac{2p}{3c} + \frac{u}{c} \right) .
\]

(30)

Transition from quintessence (phantom) to phantom (quintessence) occurs when \( \dot{\omega} < (>) 0 \), which following (30) leads to \( u_0 > (<) 2p/3 \), where \( u_0 \) is the root of (29). On the basis of the above discussion we conclude that in order to have two transitions, one from quintessence to phantom and the other from phantom to quintessence, the equation (29) must have two roots. One of these roots lies in \((0, 2p/3)\) and the other must be located in \((2p/3, 1)\). The minimum of \( \omega \) occurs at \( u = 2p/3 \) in the phantom era: at this point \( \dot{\omega} = 0 \) and \( \ddot{\omega} > 0 \).

Consider the sequence \( D(u) = \{u^3 - pu^2 - q, 3u^2 - 2pu, 6u - 2p, 6\} \); we have \( D(0) = \{-q, 0, -2p, 6\}, \) \( D(1) = \{1 - p - q, 3 - 2p, 6 - 2p, 6\} \) and \( D(2p/3) = \{-4p^3/27 - q, 0, 2p, 6\} \). The discriminant of the cubic polynomial, \( u^3 - pu^2 - q \), is \(-q(27q + 4p^3)\). If we expect this polynomial to have two roots in \((0, 1)\), the third root must also be real (\( p \) and \( q \) are real) and therefore the discriminant must be positive. But as we have seen before, \( q < 0 \), which results in \(-4p^3/27 - q < 0 \). Therefore there is only one sign change in \( D(2p/3) \). In \( D(0) \), for \( p > 0, q < 0 \) there are two sign changes. So if we assume \( 1 - p - q > 0 \), there is no sign change in \( D(1) \) (note that \( 2p/3 < 1 \)) and following the Budan–Fourier theorem
The particle versus the future event horizon in an interacting holographic dark energy model

Figure 2. $\omega$ as a function of $\Omega_d$, for $\lambda_m = 2.98, \lambda_d = 3.58$ and $c = 1$.

we conclude that there is one root in $(0, 2p/3)$ and the other root is in $(2p/3, 1)$. In brief if $p$ and $q$ satisfy

$$0 < p < 1.5, \quad q < 0, \quad \frac{4p^3}{27} + q > 0, \quad 1 - p - q > 0 \quad (31)$$

the transitions quintessence $\rightarrow$ phantom $\rightarrow$ quintessence are allowed. In this case, besides the big rip being avoided, the thermodynamic second law for the horizon is also respected: $\dot{S} > 0$, which follows from

$$\dot{R}_p = HR_p + 1 > 0. \quad (32)$$

At the phantom to quintessence transition time, $u$ has a lower bound: $2p/3$, and at the phantom to quintessence transition time we have $0 < u < 2p/3$. In the accelerating regime, $\omega < -1/3$, and $u$ is a decreasing function of time.

It is worth noting that there is no sign change in the sequence $D(p) = \{-q, p^2, 4p, 6\}$. So the root of (29), corresponding to the ratio of dark energy density to total energy density at quintessence to phantom transition, must be restricted to $u \in (2p/3, p)$. Thus by choosing an appropriate $p < 1$, one can determine $r$, in agreement with astrophysical data.

As an illustration, $\omega$ is depicted in figure (2) for $p = 0.8, q = -0.01$ corresponding to $\lambda_m = 2.98, \lambda_d = 3.58, c = 1$. The transitions occur in $u = 0.78$ ($\Omega_d = 0.61$) and $u = 0.12$ ($\Omega_d = 0.014$) for quintessence $\rightarrow$ phantom and phantom $\rightarrow$ quintessence respectively.

References

[1] Riess A G et al (Supernova Search Team Collaboration), 1998 Astron. J. 116 1009 [SPIRES]
Perlmutter S et al, 1998 Nature 391 51 [SPIRES]
Perlmutter S et al (Supernova Cosmology Project Collaboration), 1999 Astrophys. J. 517 565 [SPIRES]
The particle versus the future event horizon in an interacting holographic dark energy model

[2] Huterer D and Turner M S, 1999 Phys. Rev. D 60 081301 [SPIRES]
[3] Weinberg S, 1989 Rev. Mod. Phys. 61 1 [SPIRES]
[4] Huterer D and Cooray A, 2005 Phys. Rev. D 71 083506 [SPIRES]
[5] Tedrow B and Wagoner J R, 2006 Phys. Rev. D 74 083506 [SPIRES]
[6] Zhang X, 2006 Phys. Rev. D 74 103505 [SPIRES]
[7] Huterer D and Cooray A, 2005 Phys. Rev. D 72 043521 [SPIRES]
[8] Alam U, Sahni V and Starobinsky A A, 2004 J. Cosmol. Astropart. Phys. 18 287 [SPIRES]
[9] Wei H and Cai R, 2006 Phys. Lett. B 654 23 [SPIRES]
[10] Zlatev I, Wang L and Steinhardt P J, 1999 Phys. Rev. D 59 081301 [SPIRES]
[11] Zimdahl W, Pavon D and Chimento L P, 2001 Phys. Lett. B 521 133 [SPIRES]
[12] Wei H, Takaoka T and Yamaguchi M, 2000 Phys. Rev. D 62 023511 [SPIRES]
[13] Zimdahl W, Pavon D and Chimento L P, 2003 Mod. Phys. Lett. A 18 831 [SPIRES]

[1] Caldwell R R, Kamionkowski M and Weinberg N N, 2003 Phys. Rev. Lett. 81 3067 [SPIRES]
[2] Weinberg S, 1989 Rev. Mod. Phys. 61 1 [SPIRES]
[3] Zlatev I, Wang L and Steinhardt P J, 1999 Phys. Rev. D 59 081301 [SPIRES]
[4] Huterer D and Cooray A, 2005 Phys. Rev. D 72 043511 [SPIRES]
[5] Zimbali W, Pavon D and Chimento L P, 2003 Mod. Phys. Lett. A 18 831 [SPIRES]
[6] Wei H, Cai R G and Zeng D F, 2005 J. Cosmol. Astropart. Phys. JCAP05(2005)002 [SPIRES]
[7] Wei H and Cai R, 2006 Phys. Lett. B 654 23 [SPIRES]
[8] Alam U, Sahni V and Starobinsky A A, 2004 J. Cosmol. Astropart. Phys. JCAP06(2004)008 [SPIRES]
[9] Zimdahl W, Pavon D and Chimento L P, 2003 Mod. Phys. Lett. A 18 831 [SPIRES]
[10] Zimdahl W, Pavon D and Chimento L P, 2003 Mod. Phys. Lett. A 18 831 [SPIRES]

[1] Caldwell R R, Kamionkowski M and Weinberg N N, 2003 Phys. Rev. Lett. 81 3067 [SPIRES]
[2] Weinberg S, 1989 Rev. Mod. Phys. 61 1 [SPIRES]
[3] Zlatev I, Wang L and Steinhardt P J, 1999 Phys. Rev. D 59 081301 [SPIRES]
[4] Huterer D and Cooray A, 2005 Phys. Rev. D 72 043506 [SPIRES]
[5] Zimdahl W, Pavon D and Chimento L P, 2001 Phys. Lett. B 521 133 [SPIRES]
The particle versus the future event horizon in an interacting holographic dark energy model

[14] Li M, 2004 Phys. Lett. B 603 1 [SPIRES]
[15] Hsu S D H, 2004 Phys. Lett. B 594 13 [SPIRES]
[16] Simpson F, 2006 Preprint astro-ph/0609755
[17] Pavon D and Zimdahl W, 2005 Preprint hep-th/0511053
Pavon D and Zimdahl W, 2005 Phys. Lett. B 628 206 [SPIRES]
Guberina B, Horvat R and Nikolic H, 2007 J. Cosmol. Astropart. Phys. JCAP01(2007)012 [SPIRES]
[astro-ph/0611299]
Mohseni Sadjadi H and Honardoost M, 2006 Phys. Lett. B at press [gr-qc/0609076]
Kim K H, Lee H W and Myung Y S, 2006 Preprint gr-qc/0612112
Zhang X and Wu F, 2005 Phys. Rev. D 72 043524 [SPIRES]
Zhang X, 2005 Int. J. Mod. Phys. D 14 1597 [SPIRES]
Setare M R, 2006 Phys. Lett. B 642 1 [SPIRES]
Wang B, Zang J, Lin C, Abdalla E and Micheletti S, 2006 Preprint astro-ph/0607126
Zimdahl W and Pavon D, 2006 Preprint astro-ph/060555

[18] Davies P C W, 1987 Class. Quantum Grav. 4 L225 [SPIRES]
Davies P C W, 1988 Class. Quantum Grav. 5 1349 [SPIRES]
Bousso R, 2005 Phys. Rev. D 71 064024 [SPIRES]
Nojiri S and Odintsov S D, 2006 Gen. Rel. Grav. 38 1285 [SPIRES]
Brevik I, Nojiri S, Odintsov S D and Vanzo L, 2004 Phys. Rev. D 70 043520 [SPIRES]
Gonzalez-Diaz P F and Sigueaza C L, 2004 Nucl. Phys. B 697 363 [SPIRES]
Babichev E, Dokuchaev V and Eroshenko Y, 2004 Phys. Rev. Lett. 93 021102 [SPIRES]
Nojiri S and Odintsov S D, 2004 Phys. Rev. D 70 103522 [SPIRES]
Setare M R and Shafei S, 2006 J. Cosmol. Astropart. Phys. JCAP09(2006)011 [SPIRES]
Akbar M and Cai R, 2006 Preprint hep-th/0609128

[19] Huang G and Li M, 2004 J. Cosmol. Astropart. Phys. JCAP08(2004)013 [SPIRES]
Gong Y, Wang B and Zhang Y, 2005 Phys. Rev. D 72 043510 [SPIRES]
Wang B, Gong Y and Abdalla E, 2005 Phys. Lett. B 624 141 [SPIRES]
Wang B, Lin C and Abdalla E, 2006 Phys. Lett. B 637 357 [SPIRES]

[20] Brustein R, 2000 Phys. Rev. Lett. 84 2072 [SPIRES]
Davies P C W and Davis T M, 2002 Found. Phys. 32 1877
Izquierdo G and Pavon D, 2006 Phys. Lett. B 633 420 [SPIRES]
Wang B, Gong Y and Abdalla E, 2006 Phys. Rev. D 74 083520 [SPIRES]
Gong Y, Wang B and Wang A, 2007 J. Cosmol. Astropart. Phys. JCAP01(2007)024 [SPIRES]
Gong Y, Wang B and Wang A, 2006 Preprint gr-qc/0611155

[21] Mohseni Sadjadi H, 2007 Phys. Lett. B 645 108 [SPIRES]
[22] Mohseni Sadjadi H, 2006 Phys. Rev. D 73 063525 [SPIRES]