

# Interacting New Agegraphic Viscous Dark Energy with Varying $G$

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**Abstract** We consider the new agegraphic model of dark energy with a varying gravitational constant,  $G$ , in a non-flat universe. We obtain the equation of state and the deceleration parameters for both interacting and noninteracting new agegraphic dark energy. We also present the equation of motion determining the evolution behavior of the dark energy density with a time variable gravitational constant. Finally, we generalize our study to the case of viscous new agegraphic dark energy in the presence of an interaction term between both dark components.

**Keywords** Agegraphic · Dark energy · Viscous

## 1 Introduction

Many cosmological observations, such as SNe Ia [1–3], WMAP [4, 5], SDSS [6–8], Chandra X-ray observatory [9], etc., reveal that our universe is undergoing an accelerating expansion. To explain this cosmic positive acceleration, mysterious dark energy has been proposed. There are several dark energy models which can be distinguished by, for instance, their equation of state (EoS) ( $w = \frac{P_{de}}{\rho_{de}}$ ) during the evolution of the universe. Although the simplest way to explain this behavior is the consideration of a cosmological constant [10, 11], the known fine-tuning problem [12] led to the dark energy paradigm. The dynamical nature of dark energy, at least in an effective level, can originate from various fields, such as a canonical scalar field (quintessence) [13–16], a phantom field, that is a scalar field with a

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negative sign of the kinetic term [17–22], or the combination of quintessence and phantom in a unified model named quintom [23–30].

An approach to the problem of DE arises from the holographic principle that states that the number of degrees of freedom related directly to entropy scales with the enclosing area of the system. It was shown by 'tHooft and Susskind [31] that effective local quantum field theories greatly overcount degrees of freedom because the entropy scales extensively for an effective quantum field theory in a box of size  $L$  with UV cut-off  $\Lambda$ . Attempting to solve this problem, Cohen et al. showed [32] that in quantum field theory, short distance cut-off  $\Lambda$  is related to long distance cut-off  $L$  due to the limit set by forming a black hole. In other words the total energy of the system with size  $L$  should not exceed the mass of the same size black hole i.e.  $L^3 \rho_\Lambda \leq LM_p^2$  where  $\rho_\Lambda$  is the quantum zero-point energy density caused by UV cutoff  $\Lambda$  and  $M_p$  denotes Planck mass ( $M_p^2 = 1/8\pi G$ ). The largest  $L$  is required to saturate this inequality. Then its holographic energy density is given by  $\rho_\Lambda = 3c^2 M_p^2/L^2$  in which  $c$  is free dimensionless parameter and coefficient 3 is for convenience. More recently a new dark energy model, dubbed agegraphic dark energy has been proposed [33] (see also [34]), which takes into account the Heisenberg uncertainty relation of quantum mechanics together with the gravitational effect in general relativity. Following the line of quantum fluctuations of spacetime, Karolyhazy [35–37] proposed that the distance  $t$  in Minkowski spacetime cannot be known to a better accuracy than  $\delta t = \beta t_p^{2/3} t^{1/3}$ , where  $\lambda$  is a dimensionless constant of order unity. Based on Karolyhazy relation, Maziazhvili proposed that the energy density of metric fluctuations of Minkowski spacetime is given by [38, 39]

$$\rho_\Lambda \sim \frac{1}{t_p^2 t^2} \sim \frac{M_p^2}{t^2}, \quad (1)$$

where  $t_p$  is the reduced Planck time, and  $M_p$  is the Planck mass. The agegraphic models of dark energy have been examined and constrained by various astronomical observations [40–58].

Since we know neither the nature of dark energy nor the nature of dark matter, a microphysical interaction model is not available either. However, pressureless dark matter in interaction with holographic dark energy is more than just another model to describe an accelerated expansion of the universe. Understanding dark energy is one of the biggest challenges to the particle physics of this century. Studying the interaction between the dark energy and ordinary matter will open a possibility of detecting the dark energy. It should be pointed out that evidence was recently provided by the Abell Cluster A586 in support of the interaction between dark energy and dark matter [59, 60]. However, despite the fact that numerous works have been performed till now, there are no strong observational bounds on the strength of this interaction [61, 62]. This weakness to set stringent (observational or theoretical) constraints on the strength of the coupling between dark energy and dark matter stems from our unawareness of the nature and origin of dark components of the Universe. It is therefore more than obvious that further work is needed in this direction.

Previously, it has been shown that the interacting new agegraphic model of dark energy can cross the phantom divide [56, 57]. The phantom energy, if it exists, can cause some peculiar phenomena e.g. violates the strong energy condition,  $\rho + 3p \geq 0$ . This leads us to consider phantom energy as an imperfect fluid, implying that the phantom fluid could contain non-zero bulk and shear viscosities [63]. The bulk viscosities are negligible for non-relativistic and ultra-relativistic fluids but are important for the intermediate cases. In viscous cosmology, shear viscosities arise in relation to space anisotropy while the bulk viscosity accounts for the space isotropy [64]. Generally, shear viscosities are ignored (as

the CMBR does not indicate significant anisotropies) and only bulk viscosities are taken into account for the fluids in the cosmological context. Moreover, bulk viscosity related to a grand unified theory phase transition may lead to an explanation of the accelerated cosmic expansion [65].

Although the holographic dark energy model with varying gravitational constant has been studied in [66, 67], however, until now, in all the investigated agegraphic dark energy models a constant Newton's "constant"  $G$  has been considered. The role of  $G$ -variation will be expressed through the pure number  $G'/G \equiv \Delta_G$ , which will be extracted from observations. In particular, observations of Hulse-Taylor binary pulsar B1913 + 16 lead to the estimation  $\dot{G}/G \sim 2 \pm 4 \times 10^{-12} \text{ yr}^{-1}$  [94, 95], while helio-seismological data provide the bound  $-1.6 \times 10^{-12} \text{ yr}^{-1} < \dot{G}/G < 0$  [96]. Similarly, Type Ia supernova observations [1–3] give the best upper bound of the variation of  $G$  as  $-10^{-11} \text{ yr}^{-1} \leq \frac{\dot{G}}{G} < 0$  at redshifts  $z \simeq 0.5$  [97], while asteroseismological data from the pulsating white dwarf star G117-B15A lead to  $|\frac{\dot{G}}{G}| \leq 4.10 \times 10^{-11} \text{ yr}^{-1}$  [98]. See also [99] for various bounds on  $\dot{G}/G$  from observational data, noting that all these measurements are valid at relatively low redshifts, i.e.  $z < 3.5$ . Since the limits in  $G$ -variation are given for  $\dot{G}/G$  in units  $\text{yr}^{-1}$ , and since  $\dot{G}/G = HG'/G$ , we can estimate  $\Delta_G$  substituting the value of  $H$  in  $\text{yr}^{-1}$  [66].

Besides, there have been many proposals in the literature attempting to theoretically justified a varying gravitational constant. For example in Brans-Dicke theory the gravitational constant is replaced by a scalar field coupling to gravity through a new parameter, and it has been generalized to various forms of scalar-tensor theories [100–102], leading to a considerably broader range of variable- $G$  theories. In addition, justification of a varying Newton's constant has been established with the use of conformal invariance and its induced local transformations [103]. Finally, a varying  $G$  can arise perturbatively through a semiclassical treatment of Hilbert-Einstein action [104–106], non-perturbatively through quantum gravitational approaches within the "Hilbert-Einstein truncation" [107, 108], or through gravitational holography [109, 110].

In the light of all mentioned above, it becomes obvious that the investigation on the interacting new agegraphic dark energy models with varying gravitational constant is well motivated. In this paper, we would like to generalize, following [68], the new agegraphic viscous dark energy models to the universe with spacial curvature in the presence of interaction between the dark matter and dark energy with a varying gravitational constant,  $G$ .

## 2 New ADE with Varying Gravitational Constant

Soon after the original ADE model was introduced [33], an alternative model dubbed "new agegraphic dark energy" was proposed by Wei and Cai [69], while the time scale is chosen to be the conformal time  $\eta$  instead of the age of the universe, which is defined by  $dt = a d\eta$ , where  $t$  is the cosmic time. It is worth noting that the Karolyhazy relation  $\delta t = \beta t_p^{2/3} t^{1/3}$  was derived for Minkowski spacetime  $ds^2 = dt^2 - dx^2$  [35–39]. In case of the FRW universe, we have  $ds^2 = dt^2 - a^2 dx^2 = a^2(d\eta^2 - dx^2)$ . Thus, it might be more reasonable to choose the time scale to be the conformal time  $\eta$  since it is the causal time in the Penrose diagram of the FRW universe. The new ADE contains some new features different from the original ADE and overcome some unsatisfactory points. For instance, the original ADE suffers from the difficulty to describe the matter-dominated epoch while the new agegraphic dark energy resolved this issue [69]. The energy density of the new ADE can be written

$$\rho_D = \frac{3n^2}{8\pi G\eta^2}, \quad (2)$$

where the conformal time is given by

$$\eta = \int \frac{dt}{a} = \int_0^a \frac{da}{Ha^2}. \quad (3)$$

If we write  $\eta$  to be a definite integral, there will be an integral constant in addition. Thus, we have  $\dot{\eta} = 1/a$ . Consider a FRW universe with spatial curvature containing the new agegraphic dark energy and pressureless matter. The Friedmann equation can be written

$$H^2 + \frac{k}{a^2} = \frac{8\pi G}{3}(\rho_m + \rho_D), \quad (4)$$

where  $k$  is the curvature parameter with  $k = -1, 0, 1$  corresponding to open, flat, and closed universes, respectively. A closed universe with a small positive curvature ( $\Omega_k \simeq 0.01$ ) is compatible with observations [70–74]. If we introduce, as usual, the fractional energy densities such as

$$\Omega_m = \frac{8\pi G\rho_m}{3H^2}, \quad \Omega_D = \frac{8\pi G\rho_D}{3H^2}, \quad \Omega_k = \frac{k}{H^2a^2}, \quad (5)$$

then the Friedmann equation can be written

$$\Omega_m + \Omega_D = 1 + \Omega_k. \quad (6)$$

The fractional energy density of the new agegraphic dark energy can also be written

$$\Omega_D = \frac{n^2}{H^2\eta^2}. \quad (7)$$

We consider the FRW universe filled with dark energy and dust (dark matter) which evolves according to their conservation laws

$$\dot{\rho}_D + 3H\rho_D(1 + w_D) = 0, \quad (8)$$

$$\dot{\rho}_m + 3H\rho_m = 0, \quad (9)$$

where  $w_D = p_D/\rho_D$  is the equation of state parameter of new ADE. Taking the derivative of (2) with respect to the cosmic time and using (7) we have

$$\dot{\rho}_D = -H\rho_D \left( 2\frac{\sqrt{\Omega_D}}{na} + \frac{G'}{G} \right). \quad (10)$$

where the prime stands for the derivative with respect to  $x = \ln a$ . Inserting this equation in the conservation law (8), we obtain the equation of state parameter

$$w_D = -1 + \frac{2}{3na}\sqrt{\Omega_D} + \frac{G'}{3G}. \quad (11)$$

The equation of motion for  $\Omega_D$  can be obtained by taking the derivative of (7). The result is

$$\Omega'_D = -\Omega_D \left( 2\frac{\dot{H}}{H^2} + 2\frac{\sqrt{\Omega_D}}{na} \right). \quad (12)$$

where the dot is the derivative with respect to the time. The next step is to calculate  $\frac{\dot{H}}{H^2}$ . Taking the derivative of both side of the Friedman equation (4) with respect to the cosmic time  $t$ , and using (5)–(9) and (11), we obtain

$$2\frac{\dot{H}}{H^2} = 3(\Omega_D - 1) - \frac{2}{na}\Omega_D^{3/2} - \Omega_k + \frac{G'}{G}(1 + \Omega_k - \Omega_D) \tag{13}$$

Substituting this relation into (23), we obtain the evolution behavior of the new agegraphic dark energy

$$\Omega'_D = \Omega_D \left[ (1 - \Omega_D) \left( 3 - \frac{2}{na}\sqrt{\Omega_D} \right) + \Omega_k - \frac{G'}{G}(1 + \Omega_k - \Omega_D) \right]. \tag{14}$$

For completeness, we give the deceleration parameter

$$q = -\frac{\ddot{a}}{aH^2} = -1 - \frac{\dot{H}}{H^2}, \tag{15}$$

which combined with the Hubble parameter and the dimensionless density parameters form a set of useful parameters for the description of the astrophysical observations. Substituting (13) in (15) we get

$$q = \frac{1}{2} - \frac{3}{2}\Omega_D + \frac{\Omega_D^{3/2}}{na} + \frac{\Omega_k}{2} - \frac{G'}{2G}(1 + \Omega_k - \Omega_D). \tag{16}$$

### 3 Interacting New ADE with Varying Gravitational Constant

Next we consider the case where the pressureless dark matter and the new ADE do not conserve separately but interact with each other. Given the unknown nature of both dark matter and dark energy there is nothing in principle against their mutual interaction and it seems very special that these two major components in the universe are entirely independent. Indeed, this possibility is receiving growing attention in the literature [75–85] and appears to be compatible with SNIa and CMB data [86]. The total energy density satisfies a conservation law

$$\dot{\rho} + 3H(\rho + p) = 0, \tag{17}$$

where  $\rho = \rho_m + \rho_D$  and  $p = p_D$ . However, as stated above, both components- the pressureless dark matter and the new ADE- are assumed to interact with each other; thus, one may grow at the expense of the other. The conservation equations for them read

$$\dot{\rho}_D + 3H\rho_D(1 + w_D) = -Q, \tag{18}$$

$$\dot{\rho}_m + 3H\rho_m = Q, \tag{19}$$

where  $Q$  stands for the interaction term. Following [87] we shall assume for the latter the ansatz  $Q = \Gamma\rho_D$  with  $\Gamma > 0$  which means that there is an energy transfer from the dark energy to dark matter. This expression for the interaction term was first introduced in the study of the suitable coupling between a quintessence scalar field and a pressureless cold dark matter field [75–81]. We also assume  $\Gamma = 3b^2(1 + r)H$  where  $r = \rho_m/\rho_D$  and  $b^2$  is a coupling constant. Therefore, the interaction term  $Q$  can be expressed as

$$Q = 3b^2H\rho_D(1 + r), \tag{20}$$

where

$$r = \frac{\Omega_m}{\Omega_D} = -1 + \frac{1 + \Omega_k}{\Omega_D}. \quad (21)$$

Combining (10), (20) and (21) with (18) we obtain the equation of state parameter

$$w_D = -1 + \frac{2}{3na} \sqrt{\Omega_D} - b^2 \frac{(1 + \Omega_k)}{\Omega_D} + \frac{G'}{3G}. \quad (22)$$

If we take following [66]  $0 < G'/G \leq 0.07$  and assuming  $\Omega_D = 0.73$  and  $\Omega_k \approx 0.01$  for the present time and  $n = 4$ ,  $b = 0.1$ , we obtain  $-0.87 < w_D \leq 0.85$  which is consistent with recent observations. We can also find the equation of motion for  $\Omega_D$  by taking the derivative of (7). The result is

$$\Omega'_D = \Omega_D \left( -2 \frac{\dot{H}}{H^2} - \frac{2}{na} \sqrt{\Omega_D} \right). \quad (23)$$

where

$$2 \frac{\dot{H}}{H^2} = 3(\Omega_D - 1) - \frac{2}{na} \Omega_D^{3/2} - \Omega_k - b^2 \frac{(1 + \Omega_k)}{\Omega_D} + \frac{G'}{G} (1 + \Omega_k - \Omega_D) \quad (24)$$

Substituting this relation into (23), we obtain the evolution behavior of the interacting new agegraphic dark energy with variable gravitational constant

$$\Omega'_D = \Omega_D \left[ (1 - \Omega_D) \left( 3 - \frac{2}{na} \sqrt{\Omega_D} \right) + \Omega_k - 3b^2 (1 + \Omega_k) - \frac{G'}{G} (1 + \Omega_k - \Omega_D) \right]. \quad (25)$$

The deceleration parameter is now given by

$$q = \frac{1}{2} - \frac{3}{2} \Omega_D + \frac{\Omega_D^{3/2}}{na} + \frac{\Omega_k}{2} - \frac{3}{2} b^2 (1 + \Omega_k) - \frac{G'}{2G} (1 + \Omega_k - \Omega_D). \quad (26)$$

Again taking  $0 < G'/G \leq 0.07$  and assuming  $\Omega_D = 0.73$  and  $\Omega_k \approx 0.01$  for the present time and  $n = 4$ ,  $b = 0.1$ , we obtain  $-0.46 < q \leq 0.45$  which is again compatible with recent observational data [111].

#### 4 Interacting Viscous New ADE with Varying $G$

In this section we would like to generalize our study to the interacting viscous new agegraphic dark energy model. In an isotropic and homogeneous FRW universe, the dissipative effects arise due to the presence of bulk viscosity in cosmic fluids. The theory of bulk viscosity was initially investigated by Eckart [88] and later on pursued by Landau and Lifshitz [89]. Dark energy with bulk viscosity has a peculiar property to cause accelerated expansion of phantom type in the late evolution of the universe [64, 90–92]. It can also alleviate several cosmological puzzles like age problem, coincidence problem and phantom crossing. The energy-momentum tensor of the viscous fluid is

$$T_{\mu\nu} = \rho_D u_\mu u_\nu + \tilde{p}_D (g_{\mu\nu} + u_\mu u_\nu), \quad (27)$$

where  $u_\mu$  is the four-velocity vector and

$$\tilde{p}_D = p_D - 3H\xi, \tag{28}$$

is the effective pressure of dark energy and  $\xi$  is the bulk viscosity coefficient. We require  $\xi > 0$  to get positive entropy production in conformity with second law of thermodynamics [93]. The energy conservation equation for interacting viscous dark energy is now given by

$$\dot{\rho}_D + 3H(\rho_D + \tilde{p}_D) = -Q, \tag{29}$$

which can be written

$$\dot{\rho}_D + 3H\rho_D(1 + w_D) = 9H^2\xi - Q, \tag{30}$$

Combining (10), (20) and (21) with (30) we obtain the equation of state parameter

$$w_D = -1 + \frac{2}{3na}\sqrt{\Omega_D} - b^2\frac{(1 + \Omega_k)}{\Omega_D} + \frac{G'}{3G} + \frac{3H\xi}{\rho_D}. \tag{31}$$

If we assume  $\xi = \alpha H^{-1}\rho_D$ , where  $\alpha$  is a constant parameter, then we get

$$w_D = 3\alpha - 1 + \frac{2}{3na}\sqrt{\Omega_D} - b^2\frac{(1 + \Omega_k)}{\Omega_D} + \frac{G'}{3G}. \tag{32}$$

The equation of motion for viscous ADE is obtained as

$$\begin{aligned} \Omega'_D = \Omega_D \left[ (1 - \Omega_D) \left( 3 - \frac{2}{na}\sqrt{\Omega_D} \right) + \Omega_k - 3b^2(1 + \Omega_k) \right. \\ \left. - \frac{G'}{G}(1 + \Omega_k - \Omega_D) + 9\alpha\Omega_D \right]. \end{aligned} \tag{33}$$

### 5 Conclusions

In this work we have investigated the interacting new agegraphic viscous dark energy scenario with a varying gravitational constant. We have obtained the equation of state and the deceleration parameters for both interacting and noninteracting new agegraphic dark energy. By considering non-interacting and interacting cases we have extracted the exact differential equations that determine the evolution of the dark energy density-parameter, where the  $G$ -variation appears as a coefficient in additional terms.

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### References

1. Riess, A.G., et al. (Supernova Search Team Collaboration): *Astrophys. J.* **607**, 665 (2004). [arXiv:astro-ph/0402512](https://arxiv.org/abs/astro-ph/0402512)
2. Knop, R.A., et al. (Supernova Cosmology Project Collaboration): *Astrophys. J.* **598**, 102 (2003). [arXiv:astro-ph/0309368](https://arxiv.org/abs/astro-ph/0309368)

3. Perlmutter, S., et al. (Supernova Cosmology Project Collaboration): *Astrophys. J.* **517**, 565 (1999). [arXiv:astro-ph/9812133](#)
4. Bennett, C.L., et al.: *Astrophys. J. Suppl.* **148**, 1 (2003). [arXiv:astro-ph/0302207](#)
5. Spergel, D.N., et al.: *Astrophys. J. Suppl.* **148**, 175 (2003). [arXiv:astro-ph/0302209](#)
6. Tegmark, M., et al. (SDSS Collaboration): *Phys. Rev. D* **69**, 103501 (2004). [arXiv:astro-ph/0310723](#)
7. Seljak, U., et al.: *Phys. Rev. D* **71**, 103515 (2005). [astro-ph/0407372](#)
8. Adelman-McCarthy, J.K., et al. (SDSS Collaboration): [arXiv:astro-ph/0507711](#)
9. Allen, S.W., et al.: *Mon. Not. R. Astron. Soc.* **353**, 457 (2004). [astro-ph/0405340](#)
10. Sahni, V., Starobinsky, A.: *Int. J. Mod. Phys. D* **9**, 373 (2000)
11. Peebles, P.J., Ratra, B.: *Rev. Mod. Phys.* **75**, 559 (2003)
12. Steinhardt, P.J.: *Critical Problems in Physics*. Princeton University Press, Princeton (1997)
13. Ratra, B., Peebles, P.J.E.: *Phys. Rev. D* **37**, 3406 (1988)
14. Wetterich, C.: *Nucl. Phys. B* **302**, 668 (1988)
15. Liddle, A.R., Scherrer, R.J.: *Phys. Rev. D* **59**, 023509 (1999)
16. Zlatev, I., Wang, L.M., Steinhardt, P.J.: *Phys. Rev. Lett.* **82**, 896 (1999)
17. Caldwell, R.R.: *Phys. Lett. B* **545**, 23 (2002)
18. Caldwell, R.R., Kamionkowski, M., Weinberg, N.N.: *Phys. Rev. Lett.* **91**, 071301 (2003)
19. Nojiri, S., Odintsov, S.D.: *Phys. Lett. B* **562**, 147 (2003)
20. Onemli, V.K., Woodard, R.P.: *Phys. Rev. D* **70**, 107301 (2004)
21. Setare, M.R., Sadeghi, J., Amani, A.R.: *Phys. Lett. B* **666**, 288 (2008)
22. Setare, M.R., Saridakis, E.N.: *J. Cosmol. Astropart. Phys.* **0903**, 002 (2009)
23. Feng, B., Wang, X.L., Zhang, X.M.: *Phys. Lett. B* **607**, 35 (2005)
24. Guo, Z.K., et al.: *Phys. Lett. B* **608**, 177 (2005)
25. Li, M.-Z., Feng, B., Zhang, X.-M.: *J. Cosmol. Astropart. Phys.* **0512**, 002 (2005)
26. Setare, M.R.: *Phys. Lett. B* **641**, 130 (2006)
27. Setare, M.R., Sadeghi, J., Amani, A.R.: *Phys. Lett. B* **660**, 299 (2008)
28. Setare, M.R., Saridakis, E.N.: *Phys. Lett. B* **668**, 177 (2008)
29. Setare, M.R., Saridakis, E.N.: *J. Cosmol. Astropart. Phys.* **0809**, 026 (2008)
30. Setare, M.R., Saridakis, E.N.: *Int. J. Mod. Phys. D* **18**, 549 (2009)
31. Susskind, L.: *J. Math. Phys.* **36**, 6377–6396 (1995)
32. Cohen, A., Kaplan, D., Nelson, A.: *Phys. Rev. Lett.* **82**, 4971 (1999)
33. Cai, R.G.: *Phys. Lett. B* **657**, 228 (2007)
34. Neupane, I.P.: *Phys. Lett. B* **673**, 111 (2009)
35. Karolyhazy, F.: *Nuovo Cimento A* **42**, 390 (1966)
36. Karolyhazy, F., Frenkel, A., Lukacs, B.: In: Shimony, A., Feschbach, H. (eds.) *Physics as Natural Philosophy*. MIT Press, Cambridge (1982)
37. Karolyhazy, F., Frenkel, A., Lukacs, B.: In: Penrose, R., Isham, C.J. (eds.) *Quantum Concepts in Space and Time*. Clarendon Press, Oxford (1986)
38. Maziashvili, M.: *Int. J. Mod. Phys. D* **16**, 1531 (2007)
39. Maziashvili, M.: *Phys. Lett. B* **652**, 165 (2007)
40. Wei, H., Cai, R.G.: *Eur. Phys. J. C* **59**, 99 (2009)
41. Wei, H., Cai, R.G.: *Phys. Lett. B* **663**, 1 (2008)
42. Cui, J., et al.: [arXiv:0902.0716](#)
43. Kim, Y.W., et al.: *Mod. Phys. Lett. A* **23**, 3049 (2008)
44. Zhang, Y., et al.: [arXiv:0708.1214](#)
45. Wu, J.P., Ma, D.Z., Ling, Y.: *Phys. Lett. B* **663**, 152 (2008)
46. Kim, K.Y., Lee, H.W., Myung, Y.S.: *Phys. Lett. B* **660**, 118 (2008)
47. Wu, X., et al.: [arXiv:0708.0349](#)
48. Zhang, J., Zhang, X., Liu, H.: *Eur. Phys. J. C* **54**, 303 (2008)
49. Neupane, I.P.: *Phys. Lett. B* **673**, 111 (2009)
50. Sheykhi, A.: *Phys. Lett. B* **680**, 113 (2009)
51. Sheykhi, A.: *Phys. Lett. B* **682**, 329 (2010)
52. Sheykhi, A.: *Int. J. Mod. Phys. D* **18**(13), 2023 (2009)
53. Sheykhi, A.: *Phys. Rev. D* **81**, 023525 (2010)
54. Sheykhi, A.: *Int. J. Mod. Phys. D* **19**(3), 305 (2010)
55. Sheykhi, A.: [arXiv:0909.0302](#)
56. Setare, M.R.: [arXiv:0907.4910](#)
57. Setare, M.R.: [arXiv:0908.0196](#)
58. Wei, H., Cai, R.G.: *Phys. Lett. B* **663**, 1 (2008)
59. Bertolami, O., Gil Pedro, F., Le Delliou, M.: *Phys. Lett. B* **654**, 165 (2007). [arXiv:astro-ph/0703462](#)



60. Le Delliou, M., Bertolami, O., Gil Pedro, F.: AIP Conf. Proc. **957**, 421 (2007). [arXiv:0709.2505](#) [astro-ph]
61. Feng, C., Wang, B., Gong, Y., Su, R.K.: J. Cosmol. Astropart. Phys. **0709**, 005 (2007). [arXiv:0706.4033](#) [astro-ph]
62. Abdalla, E., Abramo, L.R.W., Sodre, L.J., Wang, B.: Signature of the interaction between dark energy and dark matter in galaxy clusters. [arXiv:0710.1198](#) [astro-ph]
63. Coles, P., Lucchin, F.: Cosmology: The Origin and Evolution of Cosmic Structure. Wiley, New York (2003)
64. Brevik, I., Gorbunova, O.: Gen. Relativ. Gravit. **37**, 2039 (2005)
65. Langacher, P.: Phys. Rep. **72**, 185 (1981)
66. Jamil, M., Saridakis, E.N., Setare, M.R.: Phys. Lett. B **679**, 172 (2009)
67. Lu, J., Saridakis, E.N., Setare, M.R., Xu, L.: J. Cosmol. Astropart. Phys. **1003**, 031 (2010)
68. Setare, M.R.: Phys. Lett. B **642**, 1 (2006)
69. Wei, H., Cai, R.G.: Phys. Lett. B **660**, 113 (2008)
70. Bennett, C.L., et al.: Astrophys. J. Suppl. **148**, 1 (2003)
71. Spergel, D.N.: Astrophys. J. Suppl. **148**, 175 (2003)
72. Tegmark, M., et al.: Phys. Rev. D **69**, 103501 (2004)
73. Seljak, U., Slosar, A., McDonald, P.: J. Cosmol. Astropart. Phys. **0610**, 014 (2006)
74. Spergel, D.N., et al.: Astrophys. J. Suppl. **170**, 377 (2007)
75. Amendola, L.: Phys. Rev. D **60**, 043501 (1999)
76. Amendola, L.: Phys. Rev. D **62**, 043511 (2000)
77. Amendola, L., Quercellini, C.: Phys. Rev. D **68**, 023514 (2003)
78. Amendola, L., Tocchini-Valentini, D.: Phys. Rev. D **64**, 043509 (2001)
79. Zimdahl, W., Pavon, D.: Phys. Lett. B **521**, 133 (2001)
80. Zimdahl, W., Pavon, D.: Gen. Relativ. Gravit. **35**, 413 (2003)
81. Chimento, L.P., Jakubi, A.S., Pavon, D., Zimdahl, W.: Phys. Rev. D **67**, 083513 (2003)
82. Setare, M.R.: Eur. Phys. J. C **50**, 991 (2007)
83. Setare, M.R.: J. Cosmol. Astropart. Phys. **0701**, 023 (2007)
84. Setare, M.R.: Phys. Lett. B **654**, 1 (2007)
85. Setare, M.R.: Phys. Lett. B **642**, 421 (2006)
86. Olivares, G., Atrio, F., Pavon, D.: Phys. Rev. D **71**, 063523 (2005)
87. Pavon, D., Zimdahl, W.: Phys. Lett. B **628**, 206 (2005)
88. Eckart, C.: Phys. Rev. **58**, 919 (1940)
89. Landau, L.D., Lifshitz, E.M.: Fluid Mechanics. Butterworth Heineman, Stoneham (1987)
90. Brevik, I., Gorbunova, O., Shaido, Y.A.: Int. J. Mod. Phys. D **14**, 1899 (2005)
91. Brevik, I., Gorbunova, O.: Eur. Phys. J. C **56**, 425 (2008)
92. Brevik, I., Gorbunova, O., Gomez, D.S.: [arXiv:0908.2882](#)
93. Zimdahl, W., Pavon, D.: Phys. Rev. D **61**, 108301 (2000)
94. Bisnovatyi-Kogan, G.S.: Int. J. Mod. Phys. D **15**, 1047 (2006)
95. Damour, T., et al.: Phys. Rev. Lett. **61**, 1151 (1988)
96. Guenther, D.B.: Phys. Lett. B **498**, 871 (1998)
97. Gaztanaga, E., Garcia-Berro, E., Isern, J., Bravo, E., Dominguez, I.: Phys. Rev. D **65**, 023506 (2002)
98. Biesiada, M., Malec, B.: Mon. Not. R. Astron. Soc. **350**, 644 (2004)
99. Ray, S., Mukhopadhyay, U.: Int. J. Mod. Phys. D **16**, 1791 (2007)
100. Bergmann, P.G.: Int. J. Theor. Phys. **1**, 25 (1968)
101. Wagoner, R.V.: Phys. Rev. D **1**, 3209 (1970)
102. Nordtvedt, K.: Astrophys. J. **161**, 1059 (1970)
103. Bekenstein, J.D.: Found. Phys. **16**, 409 (1986)
104. Shapiro, I.L., Sola, J.: J. High Energy Phys. **0202**, 006 (2002)
105. Babic, A., Guberina, B., Horvat, R., Stefancic, H.: Phys. Rev. D **65**, 085002 (2002)
106. Shapiro, I.L., Sola, J., Espana-Bonet, C., Ruiz-Lapuente, P.: Phys. Lett. B **574**, 149 (2003)
107. Reuter, M.: Phys. Rev. D **57**, 971 (1998)
108. Bonnano, A., Reuter, M.: Phys. Rev. D **65**, 043508 (2002)
109. Horvat, R.: Phys. Rev. D **70**, 087301 (2004)
110. Guberina, B., Horvat, R., Nikolic, H.: Phys. Rev. D **72**, 125011 (2005)
111. Daly, R.A., et al.: Astrophys. J. **677**, 1 (2008)