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Dark energy–dark matter interaction and putative violation of the equivalence principle from the Abell cluster A586

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Abstract

We show that the Abell cluster A586 exhibits evidence of the interaction between dark matter and dark energy and argue that this interaction implies a violation of the equivalence principle. This violation is found in the context of two different models of dark energy–dark matter interaction. We also argue, based on the spherical symmetry of the Abell cluster A586 that skewness is not the most general quantity to test the equivalence principle.

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1. Introduction

It has become rather consensual that the problem of the nature of dark energy and dark matter (hereafter DE and DM, respectively) is crucial in contemporary cosmology. Even though, observational data is fully consistent with the ΛCDM parametrization, in order to get a deeper insight into the nature of DE and DM one must consider more complex models and, in particular, the interaction of those components. However, so far no observational evidence of this interaction has been presented. In this work, we argue that study of the Abell cluster A586 exhibits evidence of the interaction between DE and DM. Furthermore, we show that this interaction implies a violation of the Equivalence Principle (EP). Our results are obtained in the context of two distinct phenomenologically viable models for the DE–DM interaction. We consider the generalized Chaplygin gas (GCG) model [1], a unified description of DE and DM, where interaction is an automatic feature of this proposal, but also a less constrained approach where DE and DM are regarded as two independent components, but interacting (see e.g. [2]). We show that interaction between DE and DM implies a violation of the EP between DM and baryons which can be detected in self-gravitating systems in stationary equilibrium. For sure, the EP—that is, the universality of free fall—is one of the cornerstones of general relativity, however its validity at cosmological scales has never been directly tested (see [3] and references therein). The EP can be expressed in terms of the bias parameter, b, defined as ratio of baryon over DM density, at a typical clustering scale (Mpc). Should the EP hold, b would be a constant over time since then all clustering species would fall equivalently under the action of gravity. Inversely, clustering should reflect the violation of the EP through a different behaviour for both species. Interaction between DM and DE induces a time evolution of b.

In this work we shall focus on the effect of interaction on clustering as revealed by the Layzer–Irvine equation. Given that the EP concerns the way matter falls in the gravitational field, considering the clustering of matter against the cosmic expansion and the interaction with DE seems to be a logical way to test its validity. In what follows we shall see that DE–DM interaction implies a departure from virial equilibrium. First, we

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will set the formalism to address the DE–DM interaction and consider two phenomenologically viable models: one based on an *ad hoc* DE–DM interaction [2], the other in the GCG with an explicit identification of the DE and DM components [4]. Our observational inferences are based on the Abell cluster A586 given its stationarity, spherical symmetry and wealth of available observations [5].

2. Quintessence model with DE–DM interaction

The Bianchi identities with coupling ζ give origin to the following homogeneous energy conservation equations:

$$\dot{\rho}_{\rm DM} + 3H\rho_{\rm DM} = \zeta H\rho_{\rm DM}, \tag{1}$$

$$\dot{\rho}_{\rm DE} + 3H\rho_{\rm DE}(1+\omega_{\rm DE}) = -\zeta H\rho_{\rm DM}. \tag{2}$$

Notice that these equations imply that the energy exchange between DE and DM is adiabatic (see e.g. [6] and references therein). Moreover, the basic assumptions used in these equations are a constant equation of state parameter $p_{\rm DE} = \omega_{\rm DE}\rho_{\rm DE}$ and the following scaling with respect DM energy density

$$\frac{\rho_{\rm DE}}{\rho_{\rm DM}} = \frac{\Omega_{\rm DE_0}}{\Omega_{\rm DM_0}} a^\eta, \tag{3}$$

for a constant η. From the time derivative of Eq. (3) inserted into Eq. (2) together with Eq. (1) yields:

$$\zeta = -\frac{(\eta + 3\omega_{\rm DE})\Omega_{\rm DE_0}}{\Omega_{\rm DE_0} + \Omega_{\rm DM_0} a^{-\eta}}. \tag{4}$$

The solution of Eq. (1) is given by

$$\rho_{\rm DM} = a^{-3}\rho_{\rm DM_0} e^{\int_1^a \zeta \frac{da}{a}} = a^{-3}\rho_{\rm DM_0}\left[\Omega_{\rm DE_0} a^\eta + \Omega_{\rm DM_0}\right]^{-\frac{(\eta+3\omega_{\rm DE})}{\eta}}. \tag{5}$$

The DE evolution is then derived from the scaling directly, or from Eq. (2) combined with the scaling:

$$\rho_{\rm DE} = a^{\eta-3}\rho_{\rm DE_0} e^{\int_1^a \zeta \frac{da}{a}} = a^{\eta-3}\rho_{\rm DE_0}\left[\Omega_{\rm DE_0} a^\eta + \Omega_{\rm DM_0}\right]^{-\frac{(\eta+3\omega_{\rm DE})}{\eta}}. \tag{6}$$

In this model, from Eq. (5) one can see that the bias parameter depends on time as follows:

$$b = \frac{\rho_B}{\rho_{\rm DM}} = \frac{\Omega_{B_0}}{\Omega_{\rm DM_0}}\left[\Omega_{\rm DE_0} a^\eta + \Omega_{\rm DM_0}\right]^{\frac{(\eta+3\omega_{\rm DE})}{\eta}}. \tag{7}$$

3. The GCG model

Let us now consider the GCG model with an explicit identification of DE and DM, as discussed in Ref. [4]. The GCG model is considered here as it fares quite well when confronted with various phenomenological tests: high precision Cosmic Microwave Background Radiation data [7], supernova data [8–10], gravitational lensing [11], gamma-ray bursts [12], cosmic topology [13] and time variation of the electromagnetic coupling [14]. In order to obtain a suitable structure formation behaviour at linear approximation, $\omega_{\rm DE} = -1$ (see [4] and references therein). For the GCG admixture of DE and DM, the equation of state is given by [1]:

$$p = -\frac{A}{\rho^\alpha}, \tag{8}$$

where A and α are positive constants. From [4], the DM and DE expressions for a constant DE equation of state are given by

$$\rho_{\rm DM} = \rho_{\rm DM_0} a^{-3(1+\alpha)}\left(\frac{\Omega_{\rm DE_0} + \Omega_{\rm DM_0}}{\Omega_{\rm DE_0} + \Omega_{\rm DM_0} a^{-3(1+\alpha)}}\right)^{\frac{\alpha}{1+\alpha}}, \tag{9}$$

$$\rho_{\rm DE} = \rho_{\rm DE_0}\left(\frac{\Omega_{\rm DE_0} + \Omega_{\rm DM_0}}{\Omega_{\rm DE_0} + \Omega_{\rm DM_0} a^{-3(1+\alpha)}}\right)^{\frac{\alpha}{1+\alpha}}, \tag{10}$$

so that we recover Eq. (3), but now with $\eta = 3(1+\alpha)$ and $\omega_{\rm DE} = -1$.

4. The Generalized Layzer–Irvine equation

Let us now turn to the cosmological gravitational collapse and its implication for the EP. The core of our approach lies on deviation of the classical virial equilibrium, in its standard Layzer–Irvine equation form. We argue that A586 data allows to establish this departure independently of the DE–DM interaction model considered. It is possible to write the energy density conservation for non-relativistic self-gravitating dust-like particles through the so-called Layzer–Irvine equation [15]. The kernel of the method is to consider the Newtonian kinetic energy, K, per unit mass, while keeping the average momentum and mass, M, constant:

$$MK = \frac{1}{2a^2}\left\langle\frac{p^2}{m}\right\rangle \propto a^{-2}, \tag{11}$$

where a is the scale factor of the Robertson–Walker metric. It then follows that:

$$\rho_K \equiv M\,dK/dV = d(MK)/dV \propto a^{-2}. \tag{12}$$

It is assumed that the mass evolution of the cluster remains constant over the course of the observation. The energy transfer between DM and DE is negligible at this point. The potential energy per unit mass derives from the definition of the auto-correlation function, $\xi(r)$, [15]

$$W = -2\pi G a^2 \rho_{\rm DM}\int dr\,\xi(r) r, \tag{13}$$

where we have replaced the background energy density by the DM energy density. After considering the DE–DM interaction, it follows that

$$W \propto a^{2+d\ln\rho_{DM}/\ln a} = a^{\zeta-1} \tag{14}$$

and hence

$$\rho_W \equiv M\,dW/dV = d(MW)/dV \propto a^{\zeta-1}. \tag{15}$$

This is the source of difference from the usual dust case. The Layzer–Irvine equation for the energies per unit volume is just a chain rule of time derivative for the energy density where the time is parameterized by the scale factor, hence:

$$\frac{d}{dt}(\rho_{\rm DM}) = \dot{a}\frac{\partial}{\partial a}(\rho_{\rm DM}) = -\left[2\rho_K + (1-\zeta)\rho_W\right]H, \tag{16}$$

from which follows

$$\dot{\rho}_{DM} + (2\rho_K + \rho_W)H = \zeta \rho_W H, \quad (17)$$

where $H = \dot{a}/a$ is the expansion rate.

Furthermore, writing in terms of the virial equilibrium factor $2\rho_K + \rho_W$ and the departure to static equilibrium, due to the DE–DM interaction, Eq. (17) becomes

$$\dot{\rho}_{DM} + H(2\rho_K + \rho_W) = -\frac{(\eta + 3\omega_{DE})H}{1 + \Omega_{DM_0}/\Omega_{DE_0} a^{-\eta}} \rho_W. \quad (18)$$

As before, it is possible to see from the equivalent of Eq. (3) for the GCG model (for which $\omega_{DE} = -1$ [4]) that one can map Eq. (18) for the generic interaction model into the GCG model via the relationship $\eta = 3(1 + \alpha)$. Next we shall apply these equations to the stationary Abell cluster A586 for which ρ_K and ρ_W can be computed, so as to compare with the observed local measurements with the homogeneous-spawned interaction term:

$$2\rho_K + \rho_W = \zeta \rho_W. \quad (19)$$

5. The Abell cluster A586

In order to estimate the coupling between DE and DM from Eq. (19) one has to find a particular cluster to compute ρ_K and ρ_W. It is convenient that the cluster is as spherical as possible and close to stationary equilibrium. Under these conditions, one can approximate the kinetic and potential energy densities as:

$$\rho_K = M \frac{d}{dV} K \simeq M \frac{K}{V} \simeq \frac{9}{8\pi} \frac{M_{\text{Cluster}}}{R^3_{\text{Cluster}}} \sigma_v^2, \quad (20)$$

$$\rho_W = M \frac{d}{dV} W \simeq M \frac{W}{V} \simeq -\frac{3}{8\pi} \frac{G}{\langle R \rangle} \frac{M^2_{\text{Cluster}}}{R^3_{\text{Cluster}}}, \quad (21)$$

where M_{Cluster} and R_{Cluster} are the cluster's total mass (galaxies, DM and intra-cluster gas) and radius, σ_v is the velocity dispersion as determined globally from weak lensing, and $\langle R \rangle$ is the mean intergalactic distance [5].

The cluster must be also relaxed, since the core of our method consists in estimating the EP violation from a deviation from the standard form of the cosmic virial theorem defined by Eq. (17) set with no interaction.

Given these constraints a particularly suitable cluster for our purpose is the Abell cluster A586 [5]. It is found that the mass profile in this particular cluster is approximately spherical and that it is a relaxed cluster, since it has not undergone any important merging process in the last few Gyrs [5]. The agreement between dynamical (velocity dispersion and X-ray) and non-dynamical mass estimates (weak-lensing) indicates that A586 is in fact a relaxed cluster.

Considering that gravitational weak lensing is independent from equilibrium assumptions about the dynamical state of the cluster, it turns out to be the best mass estimator. Therefore, in our analysis we assume [5]:

$$M_{\text{Cluster}} = (4.3 \pm 0.7) \times 10^{14}\, M_\odot \quad (22)$$

which corresponds to the total mass inside a 422 kpc radius region estimated using gravitational weak lensing.

In order to have a coherent set of data, we take for the velocity dispersion [5]:

$$\sigma_v = (1243 \pm 58)\ \text{km}\,\text{s}^{-1} \quad (23)$$

as computed from gravitational weak lensing measurements.

The mean intergalactic distance is estimated using the coordinates (right ascension-α_c and declination-δ_c) of the 31 galaxy sample provided in Ref. [5]. Given that weak gravitational lensing data concerns a 422 kpc radius spherical region and the 31 galaxies lie within a $570h_{70}^{-1}$ kpc region, one has to select from the original sample the galaxies that lie within the range of interest. Since at the cluster's distance, one arcsecond corresponds to 2.9 kpc, we select from our sample the galaxies that have α_c and δ_c such that:

$$\sqrt{(\alpha_c - \alpha_{\text{center}})^2 + (\delta_c - \delta_{\text{center}})^2} \leqslant \Delta_{\max}, \quad (24)$$

where α_{center} and δ_{center} are the coordinates of the center of the cluster and $\Delta_{\max} = 145''$ is the angular dimension corresponding to a radius of 422 kpc. From this procedure, we build a sub-sample containing 25 galaxies. From this sub-sample coordinates one can estimate the mean intergalactic distance by elementary trigonometry, the distance between any two galaxies i and j with coordinates $(\alpha_{ci}, \delta_{ci})$ and $(\alpha_{cj}, \delta_{cj})$ is given by $r_{ij}^2 = 2d^2[1 - \cos(\alpha_{ci} - \alpha_{cj}) \cos\delta_{ci} \cos\delta_{cj} - \sin\delta_{ci} \sin\delta_{cj}]$, where d is the radial distance from the center of the cluster to Earth. Therefore the mean intergalactic distance $\langle R \rangle$ is

$$\langle R \rangle = \frac{2}{N_{\text{gal}}(N_{\text{gal}} - 1)} \sum_{i=1}^{N_{\text{gal}}} \sum_{j=1}^{i} r_{ij}, \quad (25)$$

where N_{gal} is the number of galaxies in the sample. In our sub-sample, $N_{\text{gal}} = 25$ and hence we get the estimate $\langle R \rangle = 309$ kpc. Using Eqs. (22), (23) and $\langle R \rangle$ we can estimate the kinetic and potential energy densities, Eqs. (20) and (21):

$$\rho_K = (2.14 \pm 0.55) \times 10^{-10}\ \text{J}\,\text{m}^{-3}, \quad (26)$$

$$\rho_W = (-2.83 \pm 0.92) \times 10^{-10}\ \text{J}\,\text{m}^{-3}, \quad (27)$$

where the errors were computed using linear error propagation.

It is worth mentioning that

$$\frac{\rho_K}{\rho_W} \simeq -0.76 \pm 0.05, \quad (28)$$

instead of -0.5 as one would expect for a relaxed cluster considering the standard form of the cosmic virial theorem and no DE–DM interaction.

6. DE–DM interaction and putative evidence of violation of the EP

In what follows we use our estimates of ρ_K and ρ_W, Eqs. (26), (27), and the latest cosmological WMAP data [17] to show the evidence of DE–DM interaction. We also demonstrate that this interaction implies a violation of the EP between DM and baryons.

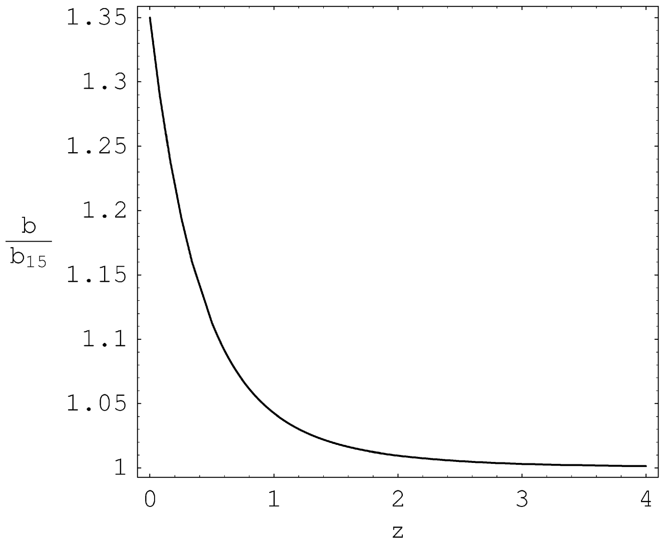

Fig. 1. Normalized gravitationally induced bias parameter as a function of the redshift, where $b_{15} \equiv b(z = 15)$, $z = 15$ being a typical condensation time.

Let us first look at the quintessence model with DE–DM interaction. From Eqs. (1) and (2) the DE–DM interaction is exhibited through a non-vanishing ζ or equivalently, from Eq. (4), by the condition $\eta \neq -3\omega_{\mathrm{DE}}$.

Thus, assuming that $\omega_{\mathrm{DE}} = -1$, $\Omega_{\mathrm{DE}_0} = 0.72$, $\Omega_{\mathrm{DM}_0} = 0.24$, one can estimate η for which Eq. (19) is satisfied for the redshift of the A586, $z = 0.1708$. We find that:

$$\eta = 3.82^{+0.18}_{-0.17}. \tag{29}$$

Thus, since Eq. (29) satisfies the condition $\eta \neq -3\omega_{\mathrm{DE}}$, one concludes that DE and DM are interacting. Notice that, as observations suggest a recent DE dominance, then $\zeta < 0$, and from there follows that $\eta > -3\omega_{\mathrm{DE}}$. This means that Eq. (29) not only suggests that DE and DM are interacting, but also, as expected, that the energy transfer flow is from DM to DE.

Let us now turn to the CGC model. With the identification of components suggested in [4], DE–DM interaction is expressed by the condition $\alpha \neq 0$. In order to see the effect of interaction in the GCG model, we proceed as before using Eqs. (19), (26) and (27), from which follows:

$$\alpha = 0.27^{+0.06}_{-0.06}. \tag{30}$$

Thus, the condition $\alpha \neq 0$ holds, meaning that the A586 data is consistent with the identification of components suggested in [4] for the CGC model. Notice that for $\alpha = 0$ the GCG model corresponds to the ΛCDM model. Moreover, it is interesting to point out that the value $\alpha \sim 0.27$ is approximately consistent with values found to match the bias and its growth from the 2dF survey (see [4] and references therein).

Evidence on a possible violation of the EP implies the time dependence of the bias parameter. We depict in Fig. 1, the evolution with redshift of the normalized bias parameter predicted by Eq. (7) where only gravitational effects are considered. Even though other astrophysical effects might affect the way DM and baryons fall under gravity, for EP purposes, gravity is the only relevant interaction that offers a clear drift on a cosmological time scale. Clearly, one expects that for large samples those effects would average out for non-cosmological drifts and thus lead to possible detection in large surveys.

Fig. 1 shows that $b(z)/b_{15}$ has undergone a sharp change in the recent past, a clear signal of the violation of the EP due to the DE–DM interaction. This abrupt variation corresponds to the period when energy transfer from DM to DE becomes significant ($z \sim 0.5$).

7. Discussion and conclusions

In this work we have argued that the properties of the A586 suggest evidence of the interaction between DE and DM. We stress that the considered models to describe the DE–DM interaction are consistent with known phenomenological constraints. We have also argued that this interaction does suggest a violation of the EP that should be detectable in large scale cluster surveys via the analysis of the time dependence of the bias parameter. We find that this violation is independent of the interaction model between DE and DM and entails a redshift evolution of bias parameter given by Eq. (7) and depicted in Fig. 1. Our conclusions are independent of the DE–DM interaction model, generic or GCG. Actually, a violation of the EP is reported to be found in other DE models [18]. For the GCG model we find that the detection of interaction precludes the ΛCDM model ($\alpha = 0$). Furthermore, the obtained value for α is approximately consistent with results for the bias and its growth obtained by the 2dF survey [4]. Consistency of our results with observational data concerning interaction [19] and further implications of the detected interaction between DE and DM, for instance, in what concerns the motion of the satellite Sagittarius galaxy [20], are discussed in [21].

It is interesting to point out that our results indicate evidence for violation of the EP between baryons and DM using data extracted from the A586, a notoriously relaxed and spherically symmetric structure. This seems to imply that the suggestion that cosmological evidence for a violation could be detected via skewness [16] does not hold. Indeed, spherical symmetry implies that skewness vanishes given that it is an odd parity spatial function. Thus, while the virial equilibrium may in principle reveal the violation of EP due to the DM–DE interaction, skewness is unable, by definition, to detect it in this particular symmetry. The spherical symmetry of A586 and our detection of violation of the EP via virial equilibrium exemplifies this point.

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