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► **To cite this version:**

Morgan Le Delliou, O. Bertolami, F. Gil Pedro. Dark Energy-Dark Matter Interaction from the Abell Cluster A586 and violation of the Equivalence Principle. 13th International Symposium on PArticles, Strings and COSmology, PASCOS-07, Jul 2007, Imperial College, London, France. hal-00172399

**HAL Id: hal-00172399**

**<https://hal.science/hal-00172399>**

Submitted on 16 Sep 2007

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# Dark Energy-Dark Matter Interaction from the Abell Cluster A586 and violation of the Equivalence Principle

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**Abstract.** We find that the Abell Cluster A586 exhibits evidence of the interaction between dark matter and dark energy and argue that this interaction suggests evidence of violation of the Equivalence Principle. This violation is found in the context of two different models of dark energy-dark matter interaction.

**Keywords:** Cosmology – dark matter – dark energy – Abell Cluster A586 – Equivalence principle

**PACS:** 98.80.-k, 98.80.Cq, 95.35.+d, 95.36.+x, 98.65.Dx, 04.20.Cv

## INTRODUCTION

Contemporary cosmology regards consensually the nature of dark energy and dark matter (hereafter DE and DM) to be crucial for a suitable description of universe's evolution and dynamics. Even though observations agree with the  $\Lambda$ CDM model, a deeper insight into DE and DM leads to more complex models – in particular, interaction between them. However, so far, no evidence of this interaction has been presented. In this work, we argue that Cluster A586 exhibits such evidence. Furthermore, we argue that this suggests evidence of violation of the Equivalence Principle (EP).

In what follows, we first set the formalism for DE-DM interaction and consider two very different, phenomenologically viable models: one based on *ad hoc* DE-DM interaction [1], the other on the generalized Chaplygin gas (GCG) model with explicit identification of DE and DM [5]. Our observational inferences are based on Cluster A586, given its stationarity, spherical symmetry and wealth of available observations [3]. We also compare our results with other cosmological observations [4].

## INTERACTING MODELS

Our results are obtained in the context of two distinct phenomenologically viable models for the DE-DM interaction: a naturally unified model, the GCG [2], but also a less constrained interacting model with constant DE equation of state (hereafter EOS) parameter  $\omega_{DE} = p_{DE}/\rho_{DE}$  (where  $p_X$  is pressure and  $\rho_X$  is energy density of  $X$ ; see e.g. [1]).

We consider first a quintessence model with constant EOS. The Bianchi conservation equations for both DE and DM read ( $H$  denoting the Hubble parameter and  $\zeta$ , the interaction strength)

$$\dot{\rho}_{DM} + 3H\rho_{DM} = \zeta H\rho_{DM}, \quad (1)$$

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

where constant EOS parameter ( $\omega_{DE}$ ), and scaling ( $\eta$ ) given by  $\frac{\rho_{DE}}{\rho_{DM}} = \frac{\Omega_{DE_0}}{\Omega_{DM_0}} a^\eta$  are assumed, as in [1] (with density parameter  $\Omega_X - \rho_X$  scaled with critical density – and  $a$ , the scale of the universe). Then, the coupling varies as  $\zeta = -\frac{(\eta+3\omega_{DE})\Omega_{DE_0}}{\Omega_{DE_0} + \Omega_{DM_0} a^{-\eta}}$  and energy densities evolve as

$$\rho_{DM} = a^{-3} \rho_{DM_0} [\Omega_{DE_0} a^\eta + \Omega_{DM_0}]^{-\frac{(\eta+3\omega_{DE})}{\eta}}, \quad \rho_{DE} = a^\eta \rho_{DE_0} \frac{\rho_{DM}}{\rho_{DM_0}}. \quad (3)$$

We turn now to the GCG model. It is defined by its unified EOS  $p_{DE} = -A/(\rho_{DM} + \rho_{DE})^\alpha$ , with  $A$  and  $\alpha$  constant, and assuming DE constant EOS parameter  $\omega_{DE} = -1$  [2]. This last splitting into DE and DM, together with Bianchi conservation imply a scaling behaviour with  $\eta = 3(1 + \alpha)$  and energy densities to be

$$\rho_{DM} = \rho_{DM_0} \frac{\rho_{DE}}{\rho_{DE_0}} a^{-3(1+\alpha)}, \quad \rho_{DE} = \rho_{DE_0} \left( \frac{\Omega_{DE_0} + \Omega_{DM_0}}{\Omega_{DE_0} + \Omega_{DM_0} a^{-3(1+\alpha)}} \right)^{\frac{\alpha}{1+\alpha}}. \quad (4)$$

## GENERALIZED LAYZER-IRVINE EQUATIONS

In this work we shall focus on the effect of interaction on clustering as revealed by the Layzer-Irvine equation. We write the kinetic and potential energy densities  $\rho_K$  and  $\rho_W$  of clustering DM in interacting models in terms of scale factor dependence

$$\rho_K \propto a^{-2}, \quad \rho_W \propto a^{\zeta-1}, \quad (5)$$

and we use DM virialization dynamics in an expanding universe described by the generalised Layzer-Irvine equation [6]

$$\dot{\rho}_{DM} + (2\rho_K + \rho_W)H = \zeta H \rho_W, \quad (6)$$

with  $\zeta$ , the coupling for the quintessence model (for the GCG, the scaling allows to just replace  $\eta = 3(1 + \alpha)$  and  $\omega_{DE} = -1$ ). At equilibrium,  $2\rho_K + \rho_W = \zeta \rho_W \neq 0$ .

## DETECTION OF INTERACTION FROM OBSERVATION OF A586

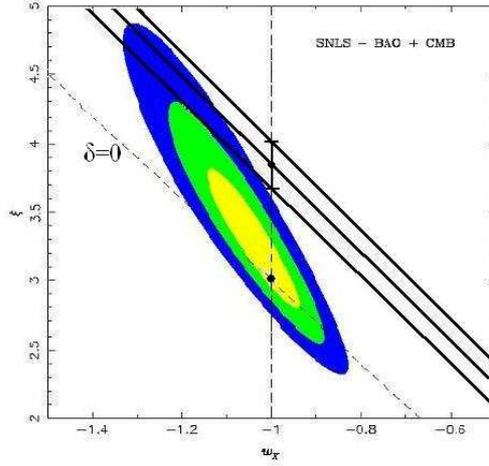
Using those models, we have interpreted observations from an Abell cluster [3] and compared it with other observations [4].

From [3], we extract: the total mass,  $M_{Cluster} = (4.3 \pm 0.7) \times 10^{14} M_\odot$  (galaxies, DM and intra-cluster gas), radius,  $R_{Cluster} = 422$  kpc at  $z = 0.1708$  (angular radius  $\Delta_{max} = 145''$ ) and cluster dispersion  $\sigma_v = (1243 \pm 58) \text{ kms}^{-1}$ , from weak lensing. From photometry, we obtain  $\langle R \rangle = \frac{2}{N_{gal}(N_{gal}-1)} \sum_{i=2}^{N_{gal}} \sum_{j=1}^{i-1} r_{ij}$ , the mean intergalactic distance<sup>1</sup>, from declinations and right assentions of a galaxy sub-sample within the projected  $\Delta_{max}$  (i.e. for galaxy  $i$ ,  $\sqrt{\alpha_{ci}^2 + \delta_{ci}^2} \leq \Delta_{max}$ ). Further assuming  $\omega_{DE} = -1$  and  $\Omega_{DE_0} = 0.72$ ,  $\Omega_{DM_0} = 0.24$  [7], we get

$$\rho_K \simeq \frac{9}{8\pi} \frac{M_{Cluster}}{R_{Cluster}^3} \sigma_v^2 = (2.14 \pm 0.55) \times 10^{-10} \text{ Jm}^{-3}, \quad (7)$$

$$\rho_W \simeq -\frac{3}{8\pi} \frac{G}{\langle R \rangle} \frac{M_{Cluster}^2}{R_{Cluster}^3} = (-2.83 \pm 0.92) \times 10^{-10} \text{ Jm}^{-3}, \quad (8)$$

<sup>1</sup> where  $r_{ij}^2 = 2d^2 [1 - \cos(\alpha_{ci} - \alpha_{cj}) \cos \delta_{ci} \cos \delta_{cj} - \sin \delta_{ci} \sin \delta_{cj}]$ ,  $\alpha_{ci} = \alpha_i - \alpha_{center}$  and  $\delta_{ci} = \delta_i - \delta_{center}$



**FIGURE 1.** Superimposition of the probability contours for the interacting DE-DM model in the  $(\omega_x, \xi)$  plane (denoted as  $(\omega_{DE_0}, \eta)$  in [8]), marginalized over  $\Omega_{DE_0}$  in [4] study of CMB, SN-Ia and BAO ( $2.66 < \xi < 4.05$  at 95% C.L.) with the results extended from [8], based on the study of A586 cluster. The  $\xi = -3\omega_x$  line corresponds to uncoupled models.

which allow us to obtain [8]

$$\eta = 3.82^{+0.18}_{-0.17} \neq -3\omega_{DE}, \quad \alpha = 0.27^{+0.06}_{-0.06} \neq 0. \quad (9)$$

Notice that  $\eta \neq -3\omega_{DE}$  signals the energy exchange between DM and DE. It is also remarkable that  $\alpha \neq 0$  which implies the GCG description is not degenerate with  $\Lambda$ CDM ( $\alpha = 0$ ). We mention that our results (see Fig.1 and [11]) are consistent with the study of [4] where DE-DM interacting quintessence are analysed for compatibility with WMAP CMB [7], SNLS SN-Ia [9] and Baryon Acoustic Oscillations in SDSS [10].

### VIOLATION OF EQUIVALENCE PRINCIPLE?

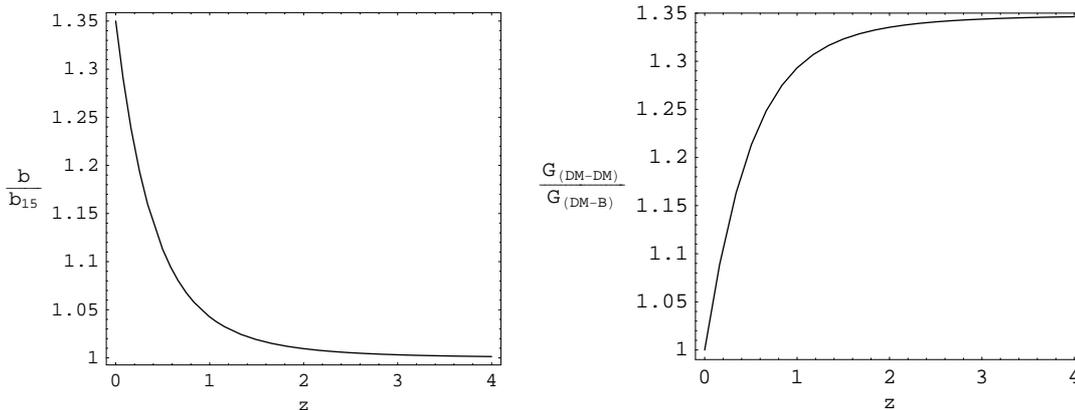
Given that the EP concerns the way matter falls in the gravitational field, considering the clustering of matter against the cosmic expansion and the interaction with DE seems to be a logical way to test its validity. Both models *predict* departure of homogeneous DM from dust behaviour and have effects that can be interpreted as violation of EP.

The non-dust evolution of DM density leads to evolution of the bias parameter,  $b = \rho_B / \rho_{DM}$ , at the homogeneous level on cosmological timescales [8] (Fig. 2a). Other astrophysical effects also affect the bias so the detection of this drift would require statistics over different  $z$  ranges.

If we attribute the non-dust  $\rho_{DM}$  to dust-like DM particles mass,

$$m_{DM}(a) = m_{DM,0} [\Omega_{DE_0} a^\eta + \Omega_{DM_0}]^{-\frac{\eta+3\omega_{DE_0}}{\eta}}, \quad (10)$$

gravity is then Baryon/DM composition dependent as seen in the two particles potential  $U_{(1-2)} = -\frac{Gm_1 m_2}{r_{12}}$ . We can now assign the time evolution to a varying G, as seen in Fig. (2b)[11], to compare with simulations of the type done by [12].



(a) (b)

**FIGURE 2.** (a) Normalized gravitationally induced bias parameter as a function of  $z$ , where  $b_{15} \equiv b(z=15)$ ,  $z=15$  is the typical condensation scale and  $b = \rho_B/\rho_{DM} = \Omega_{B_0}/\Omega_{DM_0} [\Omega_{DE_0} a^\eta + \Omega_{DM_0}]^{(\eta+3\omega_{DE})/\eta}$ . (b) Evolution with redshift of the ratio of the gravitational coupling for DM and baryons falling on a DM halo, using the varying coupling model discussed in [11], to be compared with the simulation of [12].  $G_{(DM-DM)} = G_{(DM-B)} (\Omega_{DE_0} a^\eta + \Omega_{DM_0})^{-(\eta+3\omega_{DE_0})/\eta}$ .

## CONCLUSIONS

Observations of Cluster A586 [3] suggest evidence of departure from virialization given that A586 is very spherical and relaxed (from its mass distribution and Gyrs without mergers). The generalized Layzer-Irvine equation allows to interpret this departure as interacting DE. We therefore link the observed virialization to interaction [8, 11] with two different models, consistent with known constraints [8, refs. therein]: an interacting quintessence with constant  $\omega_{DE}$  [1] and a Chaplygin gas with  $\omega_{DE} = -1$  [2].

From these models, we argue that the Equivalence Principle should be violated as they impact, for example, on the overall bias parameter [8] and on Baryon/DM asymmetric collapse [using 12, 11]. This is consistent with violation that other models have reported [13].

## ACKNOWLEDGMENTS

The work of MLeD is supported by FCT (Portugal), SFRH/BD/16630/2004 and hosted by J.P. Mimoso and CFTC, Lisbon University.

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