Observational constraints on the interaction between dark matter and dark energy

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Abstract. In this work we use the latest observations on BAO, SNIa, and $H(z)$, to constraint three models, two of them showing an explicit interaction between dark matter and dark energy. We found that using the three observational probes together, one of the interaction model (the IwCDM2) shows evidence for interaction at 2 $\sigma$. Although significant, further study is necessary to establish this claim firmly.

1. Introduction
Although the $\Lambda$CDM model has been confirmed as the model that best fits all the observational tests, since a few years, the level of precision of measurements and the increase in the number of them, have led to seriously consider a model extension [1]. Among the different ways in which we can deform the Model $\Lambda$CDM, are:

(i) To propose models where the cosmological constant is dynamic, that is, it changes with time. Among this family are the models of quintessence, for example, and from which comes the name dark energy, which is interpreted as a contribution to the matter content of the universe whose nature is unknown.

(ii) Models where the gravitational theory is modified, that is to say, it is expected to account for the effect of the cosmological constant.

(iii) Models where it relaxes one of the fundamental principles of cosmology, which is the homogeneity, openly violating the Copernican principle.

One of the models of the type (i) that has received much attention in recent years is the model of interaction between matter (DM) and dark energy (DE). Since we are unaware of the nature of DM (non-baryonic) and DE, it is not unreasonable to assume that both can be related. An exploratory form in which this occurs is by assuming that there is a transfer of energy from DE to DM. In this context, a direct interaction between these dark contributions appears as an observational viable option [2].

The interaction is usually modeled phenomenologically by modifying the conservation equations through a function $Q$,

$$\dot{\rho} + 3H\rho_m = Q, \quad (1)$$
$$\dot{\rho}_{de} + 3H(1 + \omega)\rho_{de} = -Q, \quad (2)$$
in such a way that only the sum of the contributions is conserved but not each one separately. If \( Q < 0 \) means that there is an energy transfer from DM to DE, and the opposite occurs for \( Q > 0 \).

2. The models

Here we study two models of interaction and as a reference, also the wCDM model with no interaction. Explicitly we study the cases: \( Q = 3\gamma H\rho_{de} \) that defines the model IwCDM1 and \( Q = 3\gamma H\rho_{dm} \) defining the model IwCDM2, both already studied in [9]. If \( \gamma \) is zero means there is no interaction. If \( \gamma < 0 \) indicates that there is transfer of energy from DM to DE.

As is well-known for the wCDM model the reduced Hubble function is

\[
E^2(z) = \Omega_m (1 + z)^3 + \Omega_b (1 + z)^4 + \Omega_c (1 + z)^3(1 + w), \tag{3}
\]

where \( \Omega_r = 2.469 \times 10^{-5} h^{-2} (1 + 0.2271) N_{\text{eff}} \) and \( N_{\text{eff}} = 3.04 \). In this case, the free parameters to be constrained by the observational data are: \( \Omega_m, h \) and \( w \).

For the IwCDM1 model the \( E(z) \) function is given by

\[
E^2(z) = \Omega_m (1 + z)^3 + \Omega_r (1 + z)^4 + \Omega_b (1 + z)^3 + \Omega_c \left( \frac{\gamma}{w + \gamma} (1 + z)^3 + \frac{w}{w + \gamma} (1 + z)^3(1 + w + \gamma) \right), \tag{4}
\]

where \( \gamma \) is the parameter that makes the interaction manifest. Here \( \Omega_m = \Omega_c + \Omega_b \) where \( \Omega_c \) is the non-baryonic part and \( \Omega_b \) is the baryonic one.

For the IwCDM2 model we obtain

\[
E^2(z) = \Omega_r (1 + z)^3 + \Omega_c (1 + z)^4 + \Omega_b (1 + z)^3 + \Omega_c \left( \frac{\gamma}{w + \gamma} (1 + z)^3(1 + w) + \frac{w}{w + \gamma} (1 + z)^3(1 - \gamma) \right). \tag{5}
\]

Here the free parameters are \( h, \Omega_b, \Omega_c, w \) and \( \gamma \). It is clear that for \( \gamma = 0 \) both expressions - those for IwCDM1 and IwCDM2 - reduced to that of the wCDM model.

3. The data

In this work we test the models described in the previous section using 3 types of data: Measurements of \( H(z) \), from type Ia supernovae (SNIa), and baryonic acoustic oscillations (BAO). Measurements of the Hubble function, \( H(z) \) are taken from [3], which consist of 30 data covering a range of redshift between \( z = 0.07 \) to \( z = 1.95 \). The data from SNIa are from the Joint Light-curve Analysis (JLA) [4], where the function to be minimized is

\[
\chi^2 = (\mu - \mu_{th})^T C^{-1}(\mu - \mu_{th}). \tag{6}
\]

Here \( C \) corresponds to the covariance matrix delivered in [4], and the modular distance is assumed to take the shape

\[
\mu = m - M + \alpha X - \gamma Y, \tag{7}
\]

where \( m \) is the maximum apparent magnitude in band B, \( X \) is related to the widening of the light curves, and \( Y \) corrects the color. In general, cosmology is restricted to the parameters \( M, X \) and \( Y \). The author of [4] also released the compressed version of JLA where only \( M \) is a free parameter.

In addition, we used data from baryonic acoustic oscillations (BAO). We used the results of the WiggleZ experiment [5], the distance measurements of SDSS DR7 BAO [6] and the data of the 6dFGS BAO [8]. The \( \chi^2 \) for the BAO data of WiggleZ is given by

\[
\chi^2_{\text{WiggleZ}} = (\tilde{A}_{\text{obs}} - \tilde{A}_{\text{th}}) C_{\text{WiggleZ}}^{-1}(\tilde{A}_{\text{obs}} - \tilde{A}_{\text{th}})^T, \tag{8}
\]
Where the data vector is $\bar{A}_{\text{obs}} = (0.474.0.442, 0.424)$ for an effective redshift $z = 0.44, 0.6$ and 0.73. The theoretical value corresponding $\bar{A}_{th}$ denotes the acoustic parameter $A(z)$ introduced in [7]. The inverse of the covariance is

$$ C_{Wigglesz}^{-1} = \begin{pmatrix} 1040.3 & -807.5 & 336.8 \\ -807.5 & 3720.3 & -1551.9 \\ 336.8 & -1551.9 & 2914.9 \end{pmatrix}. \quad (9) $$

Similarly for SDSS data DR7, $\chi^2$ is expressed as [6]

$$ \chi^2_{SDSS} = (\bar{d}_{obs} - \bar{d}_{th})C^{-1}_{SDSS}(\bar{d}_{obs} - \bar{d}_{th})^T, \quad (10) $$

where $\bar{d}_{obs} = (0.1905, 0.1097)$ is the data for $z = 0.2$ and 0.35. $\bar{d}_{th}$ denotes the ratio $d_z = r_s(z_d)/D_V(z)$ where $r_s(z)$ is a comoving sound horizon, and $D_V(z)$ is a distance defined in [6]. The inverse matrix is given by

$$ C_{SDSS}^{-1} = \begin{pmatrix} 30124 & -17227 \\ -17227 & 86977 \end{pmatrix}. \quad (11) $$

For the data of 6dFGS [8], there is only one point for $z = 0.106$, and the $\chi^2$ is:

$$ \chi^2_{6dFGS} = (d_z - 0.336/0.015)^2. \quad (12) $$

The total $\chi^2$ for BAO is then $\chi^2_{BAO} = \chi^2_{Wigglesz} + \chi^2_{SDSS} + \chi^2_{6dFGS}$. For settings using only the data of $H(z)$ we have added a prior of Planck [10] for the Hubble constant, $H_0 = 67.8 \pm 0.9$ km s$^{-1}$ Mpc$^{-1}$. More details of the work with the data see [11].

| $\chi^2_{min}$ | $h$ | $\Omega_m$ | $\Omega_b$ | $\omega$ | $\gamma$ |
|----------------|-----|-------------|------------|----------|---------|
| A 14.36/26     | 0.71 $\pm$ 0.09 | 0.19 $\pm$ 0.35 | $-$ | $-$ | $-$ | $-$ | $-$ |
| B 48.51/57     | 0.70 $\pm$ 0.01 | 0.23 $\pm$ 0.08 | $-$ | $-$ | $-$ | $-$ | $-$ |
| C 50.05/62     | 0.70 $\pm$ 0.01 | 0.30 $\pm$ 0.04 | 0.052 $\pm$ 0.018 | $-$ | $-$ | $-$ | $-$ |

**Table 1.** Best fit values of the cosmological parameters for the first interaction model IwCDM1 using different set of data. A using only $H(z)$ data. B using $H(z)$+SNIa. C using $H(z)$+SNIa +BAO.

| $\chi^2_{min}$ | $h$ | $\Omega_m$ | $\Omega_b$ | $\omega$ | $\gamma$ |
|----------------|-----|-------------|------------|----------|---------|
| A 14.06/26     | 0.74 $\pm$ 0.29 | 0.4 $\pm$ 0.1 | 0.04 $\pm$ 0.03 | $-$ | $-$ |
| B 48.50/57     | 0.70 $\pm$ 0.01 | 0.25 $\pm$ 0.05 | 0.0 $\pm$ 0.7 | $-$ | $-$ |
| C 50.10/63     | 0.70 $\pm$ 0.01 | 0.30 $\pm$ 0.04 | 0.08 $\pm$ 0.02 | $-$ | $-$ |

**Table 2.** Best fit values of the cosmological parameters for the first interaction model IwCDM2 using different set of data. The meaning of A, B and C is the same as in Table 1.
4. Results

In Figure 1, the 1σ and 2σ confidence boundaries for the $\Omega_m$ and $\gamma$ parameters of the IwCDM1 model are shown, using $H(z)$ measurements (left panel) and $H(z) + SNIa$ (right panel). According to the figure, the constraints imposed by the data is consistent with $\gamma = 0$, indicating that there is no preference for an interacting model. Once we add the contribution of SNIa, that is, using simultaneously data of $H(z)$ and SNIa, the confidence boundaries are reduced as shown in Figure 1. In this case, we note that the uncertainty in the determination of the parameters decreases appreciably, however, this time we notice that $\gamma = 0$ is on the edge of the region at 1σ in confidence. To conclude with the IwCDM1 model, we show also the result of the best fit using the latest measurements of BAO. The 1 and 2 sigma confidence boundaries are shown in Figure 2. Here the effect of the BAO points is clear. The confidence boundaries move along the degeneracy direction, making the best fit for $\Omega_m$ increase, and the best fit for $\gamma$ is now centered on a positive value - indicating energy transfer from dark energy to dark matter - discarding the value $\gamma = 0$ to 1 sigma.

Figure 1. We display confidence boundaries for 1σ and 2σ for the model IwCDM1 in the $\Omega_m$ and $\gamma$ parameters using $H(z)$ (left panel) and $H(z) + SNIa$ (right panel).

Figure 2. We display confidence boundaries for 1σ and 2σ for the model IwCDM1 in the $\Omega_m$ and $\gamma$ parameters using $H(z)+SNIa+BAO$. 
As a comparison with the previous results, we next show the confidence boundaries for the IwCDM2 model using only $H(z)$ data in Figure 3. As we can see, the best fit for this case looks quite similar to that shown in Figure 2, where again $\gamma = 0$ is discarded at 1 sigma and $\Omega_m$ is centered around $\Omega_m \simeq 0.3$.

![Figure 3](image_url)

**Figure 3.** We display confidence boundaries for 1$\sigma$ and 2$\sigma$ for the model IwCDM2 in the $\Omega_m$ and $\gamma$ parameters using only the data of $H(z)$.

A direct comparison with Fig. 1 for the previous case, we notice that this time the dispersion is lower, although the best fit value for $\Omega_m$ is relatively high (see Table II). We notice that already with only the data of $H(z)$ is seems clear a slight preference for a value $\gamma > 0$.

By plotting the contours for the IwCDM2 model using $H(z)$+SNIa we obtain the contours of Figure 4. Clearly the best fit for this model is consistent with no interaction. As can be notice in Table II, the best fit for $H_0$ decrease, and $\Omega_m$ takes a value closer to the one for the $\Lambda$CDM model. In this way, the addition of SNIa leads to $\gamma = 0$.

Now adding the BAO points we find a preference for interaction even valid at 2$\sigma$, as can be see from Table II and Fig. 5. Although this study does not incorporate dynamical constraints, as those from perturbations, our results seems to indicate a chance to find evidence for a non-zero

![Figure 4](image_url)

**Figure 4.** We display confidence boundaries from 1$\sigma$ to 4$\sigma$ for the IwCDM2 model in the $\Omega_m$ and $\gamma$ parameters using $H(Z)$+SNIa.
interaction term in the recent cosmological evolution.

Taking into account the results obtained, it is clear that it is necessary to add new observational tests to be more conclusive, mainly because the models have 5 free parameters. This work is in progress.

5. Discussion

Using the data, $H(z) + $ SNIa + BAO, the model IwCDM1 discards the solution $\gamma = 0$ to 1 sigma, whereas in the same case, the model IwCDM2 discards the solution $\gamma = 0$ at 2 sigma, clearly consistent with the existence of interaction. This result is in conflict with what was published in [9] where the authors found that in both models the data they used indicated no interaction. For $H(z) + $ SNIa, the analysis also does not show conclusive positive evidence, however, the evidence for interaction seems slightly larger in the IwCDM2 model than in IwCDM1. Finally, using only $H(z)$ data the evidence of interaction is clearly greater in the IwCDM2 model than in IwCDM1, as can be seen by comparing Figures 1 and 3. Clearly it is necessary to add new observational tests to be more conclusive in this respect.

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