Low redshift probes and coupled dark matter-dark energy models

Olga Mena
Instituto de Fisica Corpuscular, IFIC, CSIC and Universidad de Valencia, Spain
E-mail: omena@ific.uv.es

Abstract. Coupled cosmologies, in order to satisfy CMB constraints, predict values for the cosmological parameters today which may differ substantially from the parameters values within non-interacting cosmologies. In order to fit high-precision CMB data available today, coupled cosmologies can hide their effects at very low redshifts. Therefore, low redshift probes are highly complementary and thus powerful to constrain interacting dark sector models. In this talk we focus on near-universe, low-redshift constraints in a variety of coupled dark matter-dark energy models. We find that current data constrain the dimensionless coupling to be $|\xi| < 0.2$. We also explore the forecasts for future low redshift probes.

1. Introduction
Cosmological probes indicate that the universe we observe today possesses a flat geometry and a mass energy density made of $\sim 30\%$ baryonic plus cold dark matter and $70\%$ dark energy, responsible for the late-time accelerated expansion. While the $\Lambda$CDM model (a flat universe with a cosmological constant) provides a well fit to current observational data, there exist also dynamical options, as the quintessence fluid, in which a cosmic scalar field is slowly approaching its ground state. This quintessence field, in principle, may couple to other fields in nature. Observations strongly constrain the couplings to ordinary matter [1]. However, interactions within the dark sectors, i.e. between dark matter and dark energy, are still allowed by observations [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]. In this talk, based on a recent work [15], we explore the phenomenology of coupled models and consider what type of low-redshift observations are most suitable to improve present constraints.

1.1. Classification of dark coupled models
At the level of the stress-energy tensor it is always possible to introduce an interaction between the fluids of the dark sector in the following way [16]:

$$\nabla_\mu T^\mu_{(dm)\nu} = Q_\nu \quad \text{and} \quad \nabla_\mu T^\mu_{(de)\nu} = -Q_\nu. \quad (1)$$

The 4-vector $Q_\nu$ governs the energy-momentum transfer between the dark components and $T^\mu_{(dm)\nu}$ and $T^\mu_{(de)\nu}$ are the energy-momentum tensors for the dark matter and dark energy fluids, respectively. In the first family of models we consider [15] (DEvel), the momentum exchange $Q_\nu$ is parallel to the dark energy four velocity $u^\nu_{(de)}$. In the second family of models (DMvel), $Q_\nu$ is parallel to the dark matter four velocity $u^\nu_{(dm)}$ [15]. DEvel models include all quintessence
coupled models and are effectively "modified gravity" models, implying the presence of a "fifth force" effect (only for the dark matter), that is, a violation of the equivalence principle. For both DEvel and DMvel models the evolution equations for the dark matter and dark energy background energy densities reduce to:

\[ \dot{\rho}_{\text{dm}} + 3H \rho_{\text{dm}} = Q, \]

\[ \dot{\rho}_{\text{de}} + 3H \rho_{\text{de}} (1 + w) = -Q. \]

where the dot indicates derivative with respect to conformal time \( d\tau = dt/a \), \( H = \dot{a}/a \) and \( w \) is the dark-energy equation of state. For \( Q > 0 \), the energy flows from the dark energy system to dark matter one. For \( Q < 0 \), the energy flow is reversed. For each of the two families DEvel and DMvel, we propose the definition of two sub-classes of models. In class I models, \( Q \propto \rho_{\text{dm}} \), while in class II models, \( Q \propto \rho_{\text{de}} \).

Notice that the expansion history does not depend on the choice DEvel or DMvel. However, even if DMvel and DEvel models provide the same background history, the perturbation evolution is dramatically different. Therefore, while geometrical probes alone are unable to distinguish among the two of them, growth of structure will make these two models fundamentally different. In the Newtonian gauge and neglecting dark energy perturbations, we obtain, for the dark matter perturbations, at linear order

\[ \dot{\delta}_{\text{dm}} = -(\theta_{\text{dm}} - 3\Phi) + \frac{Q}{\rho_{\text{dm}}} \left( \frac{\delta Q}{Q} - \delta_{\text{dm}} + \Psi \right), \]

\[ \dot{\theta}_{\text{dm}} = -H \theta_{\text{dm}} + (b - 1) \frac{Q}{\rho_{\text{dm}}} \theta_{\text{dm}} + k^2 \Psi, \]

see [15], where \( b = 0 \) refers to DEvel models and \( b = 1 \) refers to DMvel models. Notice that the Euler equation Eq. (5) for the dark matter fluid is only modified in the first family of models (DEvel) considered here, where \( Q_\nu \propto w^{(\text{de})}_\nu \), violating therefore the weak equivalence principle. Another aspect of coupled models is that they can show non adiabatic, early time instabilities [7, 8, 17, 10, 9, 18, 13] due to the dark coupling term which appears in the dark energy pressure perturbations. In the following, we shall restrict our analysis to coupled models which satisfy the stability criterion of Ref. [10] and therefore are free of early-time, non adiabatic instabilities.

2. Dark coupled models versus \( w(z) \) cosmologies

We study uncoupled models with a dynamical dark energy component \( \tilde{w}(z) \) versus interacting DMvel and DEvel class II cosmologies with \( Q = \xi H \rho_{\text{de}} \) (with \( \xi < 0 \), in order to avoid early-time instabilities). We investigate how to distinguish among them, even if the background evolution in these cosmologies is identical.

Figure 1 from Ref. [15] illustrates the values of \( \Omega_{\text{dm}}^{(0)} h^2 \) necessary to fit WMAP 5 year angular diameter distance data, i.e. the first acoustic peak position [19], as a function of the dimensionless coupling constant \( \xi \). We analyze now the linear growth in the three possible cosmologies that lie along the one-dimensional degeneracy defined by Fig. 1. The three possible cosmologies are: a) an uncoupled, albeit dynamical dark energy cosmology, with a varying equation of state \( \tilde{w}(z) \), b) the coupled class II (\( Q \propto \rho_{\text{de}} \)) DMvel model with constant \( w = -0.9 \) and c) the coupled class II DEvel model. While in the DMvel model the baryon densities and velocities nearly trace those of the dark matter, this is not the case for the DEvel model. We consider observables probed by lensing (\( \propto \Omega_{\text{dm}} \delta_{\text{dm}} \), if one ignores geometrical factors) and linear peculiar velocities (\( \propto \theta_{\text{dm}} \)). Figure 2, from Ref. [15], shows the ratio of the values of \( \Omega_{\text{dm}} \delta_{\text{dm}} \) and \( \theta_{\text{dm}} \) in cases b) and c) to their values in an uncoupled model with the same background expansion history. In both the
DMvel and the DEvel models the dark coupling can, in principle, be distinguished from a generic, uncoupled, dark energy described by \( \bar{w}(z) \) with perturbations growing as in standard GR. Note however that in the DMvel model GR is not modified. Although extremely small in this example, this class of models displays a mis-match between the reconstructed expansion history and the growth of structures, representing an exception to the commonly accepted interpretation that such a mis-match would be a tell-tale sign of modification of GR.

2.1. Matter abundance in voids

The matter content in voids has received recent attention (see e.g. Refs. [20, 21] and references therein) because it seems that the voids are more empty than expected from ΛCDM model predictions. Reference [21] argue that in the local volume, at a distance from us of about 10 Mpc, there are too few small galaxies with circular velocities \( V_c \) below \( \sim 35 \) km/s. They estimate a factor 10 discrepancy with the ΛCDM model predictions. Coupled models in which a given amount of dark matter per unit volume turns into dark energy would provide a mechanism to clear dark matter (and galaxies) from the voids. On the other hand, the void phenomenon disfavors coupled models in which the dark matter content per unit volume is enhanced. We use [15] recent void results to derive constraints on DMvel and DEvel class II models where \( Q = \xi H \rho_{de} \). Figure 1 shows the current cold dark matter energy density in the universe as a function of the coupling for the former dark sector interaction necessary to fit WMAP 5 year data [19]. Notice that from the figure, \( \xi > -0.6 \) in order to not to have voids completely empty of matter. It is possible to improve this first limit if we assume that dark matter halos associated to galaxies with circular velocities below \( 35 \) km/s are depleted by a factor of 10. After transforming the velocity function into a mass function using spherical collapse, we find that the total dark matter mass in voids can at most be depleted by 20% [15]. This translates into a lower bound for the coupling of \( \xi = -0.2 \), see Fig. 1.

**Figure 1.** Extracted from Ref. [15], see text for details.
Figure 2. (From Ref. [15]) The ratio of the amplitude of dark matter peculiar velocities, $\theta_{dm}$, and the lensing signal, $\Omega_{dm}\delta_{dm}$ in coupled models compared to models with standard GR growth with identical expansion histories (labelled with NC for “Not Coupled”). The curves show $\xi = 0, -0.1, ..., -0.6$.

2.2. Constraints from the peculiar velocity field

The velocity field offers a test of the growth of structure, which is complementary to galaxy clustering, as, for example, is less sensitive to non-linearities and bias. Below we consider constraints that can be obtained from present bulk flow data in the local universe and forecasted constraints achievable from future galaxy redshift surveys. Recently Watkins et al. [22] have reported the observation of anomalously large bulk flows on $100 h^{-1}$ Mpc scales. In a Gaussian window of radius $50 h^{-1}$ Mpc, they find a coherent bulk motion of $407 \pm 81$ km/s in conflict with the $\Lambda$CDM expectation of $\sim 200$ km/s at the 2$\sigma$ level. Reference [23] pointed out that these results, if confirmed, would favour models with a growth of perturbations larger than $\Lambda$CDM model predictions. In Ref. [15] we study the bulk flow results for the DMvel and DEvel class II models ($Q \propto \rho_{de}$) as a function of the coupling $\xi$. While the DMvel model has dark matter peculiar velocities which are similar to those of non interacting models (the Euler equation is unmodified in the DMvel case), for the DEvel model values of the coupling $\xi < -0.35$ lead to an effective $3 \sigma$ level deviation from observations, assuming that the galaxy peculiar velocities trace the dark matter peculiar velocity field, see Ref. [15] for a detailed discussion of the topic.

A different velocity related probe arises from redshift space distortions [24, 25], which provide a measurement of the growth of structure through the quantity $f\sigma_8$, being $f$ the logarithmic derivative of the dark matter growth factor and $\sigma_8$ the rms matter fluctuations in spheres of 8 $h^{-1}$ Mpc. Figure 3 from Ref. [15] illustrates the current and future constraining power of this method, where the red crosses show the $f\sigma_8$ predictions for the DMvel class I coupled model of Ref. [12]. The blue triangles (squares) refer to the predictions of the DMvel (DEvel) class II model explored here $Q = \xi H \rho_{de}$, with $\xi = -0.5$ and $w = -0.9$. The black circles in the first panel of Fig. 3 represent current $f\sigma_8$ measurements [25], in the other two panels they show the $f\sigma_8$ forecasts for BOSS and EUCLID-like galaxy surveys (which also include future Planck CMB experiment information, see Ref. [15] for more details), assuming a $\Lambda$CDM fiducial cosmology. Notice that the $f\sigma_8$ values for the DMvel class I model are smaller than current observations. However, current errors on $f\sigma_8$ measurements are large and do not rule out these models at a
high significance level. While the predictions for the DMvel class II model are very close to those of a non interacting model, DEvel class II models will lead to huge values of $\tilde{f} \sigma_8$ especially at low redshifts, when dark energy starts to be dominant and the effect of the energy-momentum transfer starts to be important in the dark matter velocity differential equation. Such an effect can not be obtained in the two DMvel class I and class II models explored here because the Euler equation for the dark matter velocity is not modified in these interacting cosmologies. In the DEvel class II model, couplings $\xi < -0.4$ will be ruled out at more than $3\sigma$ with existing $\tilde{f} \sigma_8$ data. Accurate measurements of $\tilde{f} \sigma_8$ from future BAO surveys as BOSS or EUCLID may rule out significantly the form of couplings explored above, see the central and right panels of Fig. 3.

2.3. Weak equivalence principle constraints

Kesden and Kamionkowski (K&K) [26, 27], analyzed the consequences of WEP violation for dark-matter on galactic scales, focusing on dark-matter dominated satellite galaxies orbiting much larger host galaxies. They inferred that a difference among dark matter and baryonic accelerations larger than 10% is severely disfavoured. In Ref. [15] we have shown that for the DEvel model $Q_\nu = \xi H \rho_{de} u_\nu$ couplings $\xi$ smaller than $\sim -0.01$ are strongly disfavoured by K&K numerical analysis.

3. Summary

We summarize the classification and current constraints on dark coupling models in Fig. 4, where $d_L$ denotes the luminosity distance as obtained from e.g. Supernovae Ia observations and $D_a$ denotes the angular diameter distance as measured e.g., by angular BAO.

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### Table: DEvel vs DMvel

| DEvel | DMvel |
|-------|-------|
| **GR** | **WEPV** | **GR** |
| $\propto \rho_{dm}$ | $\propto \rho_{de}$ | $\propto \rho_{dm}$ | $\propto \rho_{de}$ |
| Euler eq. | Euler and continuity eqs | background only | continuity eq. |
| Coupled quintessence |  |  |  |
| $\xi < 0$ | or $w(z)$ | $w_{\text{const.}} > -1$ | $w_{\text{const.}} > -1$ |
| yes | yes | tiny | v. small |
| WEP tests | Pec. Velocities | $H(z)$, dL, Da | Pec. velocities |
| $|\beta| < 0.2$ | voids | $\equiv w(z)$ fluid model | voids |
| $-0.2 < \xi < 0$ | $-0.3 < \frac{\Gamma}{H_0} < 0.15$ | $-0.2 < \xi < 0$ |

Identity in background
Modifications compared to LCDM
Ensure stability
Mis-match Expansion/growth
Key observables
Current constraints

**Figure 4.** Extracted from Ref. [15].

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