New Evidence for Interacting Dark Energy from BOSS

E. Abdalla,1 Elisa G. M. Ferreira,2 Jerome Quintin,2 and Bin Wang3

1Instituto de Física, Universidade de São Paulo, C.P. 66318, 05315-970, São Paulo, SP, Brazil
2Department of Physics, McGill University, Montréal, QC, H3A 2T8, Canada
3Department of Physics and Astronomy, Shanghai Jiao Tong University, 200240 Shanghai, China

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In this Letter we show that an interaction between dark matter and dark energy is favored by the most recent large scale structure observations. The result presented by the BOSS-SDSS collaboration measuring the baryon acoustic oscillations of the Ly-α forest from high redshift quasars indicates a 2.5σ departure from the standard ΛCDM model. This is the first time that the evolution of dark energy at high redshifts has been measured and the current results cannot be explained by simple generalizations of the cosmological constant. We show here that a simple phenomenological interaction in the dark sector provides a good explanation for this deviation, naturally accommodating the Hubble parameter obtained by BOSS, $H(z=2.34) = 222 \pm 7$ km s$^{-1}$ Mpc$^{-1}$, for two of the proposed models with a positive coupling constant and rejecting the null interaction at more than 2σ. For this we used the adjusted values of the cosmological parameters for the interacting models from the current observational data sets. This small and positive value of the coupling constant also helps alleviate the coincidence problem.

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Introduction.—One of the biggest challenges in cosmology and astrophysics nowadays is to understand the nature of the two most abundant components of the universe: dark energy and dark matter. These are usually described as two independent components where dark matter is responsible for most of the non-relativistic matter in the universe and dark energy is responsible for the late time acceleration of our universe, which is described by a cosmological constant in the ΛCDM model. This standard model is widely used to describe the cosmological evolution of the universe [1], and it fits very well the current observational data. However, this model has some theoretical and observational challenges (see, e.g., [2]) that open the way for alternative models of dark energy.

Recently the BOSS experiment of the SDSS collaboration presented a new evidence against the ΛCDM model [3] based on the measurements of the BAO flux-correlation function of the Lyman alpha (Ly-α) forest from 158,401 quasars at high redshifts ($2.1 \leq z \leq 3.5$). Comparatively to previous experiments, they provide the line of sight and tangential BAO components, and this allows one to determine the angular distance and the Hubble distance independently. Their results indicate a deviation from ΛCDM of the Hubble parameter and of angular distance at an average redshift of 2.34 (1.8σ and 1.6σ deviations from Planck+WMAP and ACT/SPT respectively). Assuming a ΛCDM universe, this implies a negative energy density for the dark energy component, $\rho_{DE}(z=2.34) = \rho_{DE}(0) \times 1.2 \pm 0.8$, which is 2.5σ away from the expected value. We point out that BOSS is not optimized to observe quasars at such high redshifts. However, if more data or other experiments show that this discrepancy stands, then it would indicate that ΛCDM needs to be revised. Its simplest generalization would consist in allowing for dynamical dark energy (see [4] for a review), but this would not be enough to fix this discrepancy. This may lead one to study very exotic forms of dark energy.

A simpler solution is to consider interacting dark energy. Indeed, dark energy could couple to gravity, neutrinos, or dark matter since its effects have only been detected gravitationally. Interaction with baryonic matter (or radiation) has very tight constraints from observations and must be very small or negligible. In this sense, we are interested in models in which dark energy interacts with the dark matter component. In a field theory description of those components, this interaction is allowed and even mandatory [5, 6]. However, the main motivation to introduce such an interaction is to alleviate the coincidence problem, which can be done given an appropriate interaction.

Since the nature of the dark sector is unknown, the study of these coupled dark energy models is challenging. Many different models of this interaction have been studied in the literature from the point of view of either interacting field theory or phenomenology (for a classification of those models, see [7]). As an example of phenomenological study, one can consider holographic dark energy or a quintessence field interacting with a dark matter fluid [8, 11]. There are also attempts to develop Lagrangian models where one postulates an interaction between the scalar field, playing the role of dark energy, and a fermionic field, playing the role of dark matter [5, 12, 13] (see, however, [14]).

Recently, there has been studies of interacting dark energy models in light of new observations [10]. However, we note that there has been only little exploration of the consequences of the results from BOSS in the literature [17, 19], and thus, it is interesting to see what are
the phenomenological implications for interacting dark energy. Since this model allows for one of the components to decay into the other, we claim that energy flow from dark energy to dark matter implies a smaller amount of dark matter in the past, thus accommodating for the value of the Hubble parameter at $z = 2.34$ found by BOSS and still maintaining the cosmology today close to ΛCDM. We will perform this comparison by showing that the observational value of the Hubble parameter from quasars given by the BOSS collaboration, $H(2.34) = 222 \pm 7$ km s$^{-1}$ Mpc$^{-1}$, is consistent with the interacting model with a positive coupling constant to a better precision than ΛCDM. We will use the recently obtained cosmological parameters from Planck data for the phenomenological interacting model studied in [20]. Furthermore, comparing cosmological parameters obtained from different data sets, we will discuss the viability of the interacting models from different complementary observations.

The Model—Given the energy conservation of the full energy-momentum tensor, we can suppose that the fluid equations representing dark energy (DE) and dark matter (DM) are not conserved separately. In a Friedmann-Robertson-Walker universe, we take

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

and all other components follow the standard conservation equations. In the above equations, $\rho_{DM}$ and $\rho_{DE}$ are the energy densities for dark matter and dark energy, respectively; $\omega_{DE} = \rho_{DE}/\rho_{DE}$ is the equation of state of dark energy, considered constant in this work; and $Q$ indicates the interaction between dark energy and dark matter. One can take the Taylor expansion of the general interaction term $Q(\rho_{DM}, \rho_{DE})$, and thus, it can be represented phenomenologically as $Q \approx 3H(\xi_1 \rho_{DM} + \xi_2 \rho_{DE})$, where the coefficients $\xi_1$ and $\xi_2$ are to be determined by observations [11, 21]. Following our definition, if $Q > 0$, then dark energy decays into dark matter, and for $Q < 0$, the energy flow is in the opposite direction. The first case is consistent with the requirement that the energy density for dark energy must be of the same order as the one for dark matter for a longer period of time in order to alleviate the coincidence problem.

The validity of the phenomenological interacting dark energy model was studied in [13] where it was found that the curvature perturbation can always be stable when the interaction is proportional to the energy density of dark energy, i.e. where $\xi_1 = 0$ while $\xi_2 \neq 0$. This is true for $-1 < \omega_{DE} < 0$ (we call this Model I) and for $\omega_{DE} < -1$ (Model II). For the interaction proportional to the dark matter energy density ($\xi_1 \neq 0$ while $\xi_2 = 0$), the curvature perturbation is only stable when the constant $\omega_{DE}$ is smaller than $-1$, which we call Model III. The models are summarized in Table I.

| Model | $Q$ | $DE$ EoS |
|-------|-----|----------|
| I     | $\xi_1 H \rho_{DE}$ | $-1 < \omega < 0$ |
| II    | $3 \xi_1 H \rho_{DE}$ | $\omega < -1$ |
| III   | $3 \xi_1 H \rho_{DM}$ | $\omega < -1$ |

In this framework, the Friedmann equations can be written as

$$H^2(z) = \frac{8\pi G}{3} \left[ \rho_{DE}(z) + \rho_{DM}(z) + \rho_b(z) \right],$$
$$\dot{H} = -\frac{4\pi G}{H} \left[ \rho_{DM}(z) + \rho_b(z) + (1 + \omega_{DE})\rho_{DE}(z) \right],$$

where we are considering a universe composed of only dark energy, dark matter, and baryons. We will use this to construct the Hubble parameter for each of the interacting models and compare it with the Hubble parameter inferred from the BOSS quasar data.

For Models I and II, the energy densities for dark energy and dark matter behave as $[10]$

$$\rho_{DE} = (1 + z)^{3(1 + \omega_{DE} + \xi_2)} \rho_{DE}^0,$$
$$\rho_{DM} = (1 + z)^3 \left[ \frac{\xi_2 (1 - (1 + z)^{3(\xi_2 + \omega_{DE})}) \rho_{DE}^0}{\xi_2 + \omega_{DE}} + \rho_{DM}^0 \right],$$

where the superscript 0 indicates quantities measured today. The baryonic density is given by the standard expression, proportional to $(1 + z)^3$. For Model III, the evolution of the energy densities is given by $[10]$

$$\rho_{DE} = (1 + z)^{3(1 + \omega_{DE})} \left( \rho_{DE}^0 + \frac{\xi_1 \rho_{DM}^0}{\xi_1 + \omega_{DE}} \right),$$
$$- \frac{\xi_1}{\xi_1 + \omega_{DE}} (1 + z)^{3(1 - \xi_1)} \rho_{DM}^0,$$
$$\rho_{DM} = \rho_{DM}^0 (1 + z)^{3 - 3\xi_1}.$$

One can see from these equations that if there is an energy flow from dark energy to dark matter, then the energy density for dark matter is always smaller than what one would expect in the standard ΛCDM model. Since $\rho_{DM}$ is the dominant contribution in the Friedmann equations at higher redshifts and since observations indicate that $\omega_{DE}^0 \approx -1$, one can see from Eq. (3) that the interaction implies a smaller Hubble parameter in the past.

Furthermore, this helps alleviate the coincidence problem which is the fact that we do not understand why the energy densities of dark energy and dark matter are so close today. As it can be seen in [22], a positive coupling constant implies that the quantity $r \equiv \rho_{DM}/\rho_{DE}$ decreases at a slower rate in the interacting model than in the ΛCDM model. This makes the energy density of
dark energy closer to the one of dark matter in the past, giving us a better understanding of their closer values today.

**Analysis.**—The goal is to test whether the measured value of the Hubble parameter by the BOSS collaboration, $H(2.34) = 222 \pm 7$ km s$^{-1}$ Mpc$^{-1}$, can be accommodated by the phenomenological interacting models introduced above. From this perspective, we compare the Hubble parameter constructed theoretically with its observational value at $z = 2.34$ and test the null interaction hypothesis, i.e. ΛCDM.

In order to compute the value of the Hubble parameter, one needs several cosmological parameters such as $H_0$, $Ω_{DE}^0$, $Ω_{DM}^0$, and $Ω_k^0$. We thus construct $H(z)$ by using the adjusted values of these cosmological parameters from the data analysis done for the interacting model in [20] using Planck, BAO, SNeIa, and $H_0$ data. We compare this with the values used by the BOSS collaboration listed in Table I which are obtained from the Planck analysis for the ΛCDM model. We then examine what complementary constraint on the strength of the interaction between dark energy and dark matter one can obtain from the new BOSS result.

**TABLE II:** Cosmological parameters used by the BOSS collaboration

| Parameter | Bestfit | $\sigma$ |
|-----------|---------|----------|
| $h$       | 0.706   | 0.032    |
| $Ω_{DM}^0 h^2$ | 0.143   | 0.003    |
| $Ω_{DE}^0$ | 0.714   | 0.020    |
| $Ω_k^0 h^2$ | 0.02207 | 0.00033  |

We start by analyzing the interacting Model I. In [20], this model was studied for two different cases. Case 1 considered $Ω_{DE} = -0.999$ as a fixed value. This model was analyzed using the Planck data alone and the best fit to the cosmological parameters can be found in Table V of [20]. Case 2 treated $Ω_{DE}$ as a free parameter adjusted using the Planck+BAO and Planck+BAO+SNeIa+$H_0$ data. Table X of [20] contains the cosmological parameters for this case.

For Case 1, we compute $H(z = 2.34)$ using (2) and (4). The result can be seen in Fig. 1 where we plot the Hubble parameter at $z = 2.34$ with respect to the coupling constant $ξ_2$. The two lines indicate two different sets of cosmological parameters: the purple line shows the adjusted parameters for Case 1 in [20], and the dotted red line is constructed using the parameters from Table I adjusted for ΛCDM.

As we can see in the figure, the curves are in accordance with the Hubble parameter inferred by BOSS, indicated by the dotted gray line and by the 1σ and 2σ shaded areas, for a positive coupling constant. We reject a zero coupling constant at more than 2σ for the purple line and at a slightly smaller significance for the parameters adjusted without interaction (the dotted red line). This indicates that with a positive coupling constant we are able to explain in a very simple way a smaller value for the Hubble parameter in the past, which is not possible with ΛCDM, dynamical dark energy, or without requiring a very exotic dark energy component. The fact that we obtain a positive coupling constant is crucial, because only positive values help alleviate the coincidence problem. Thus, this model gives a natural explanation for the energy densities of the dark components at low redshifts, where they are of the same order, and also at high redshifts, since they explain the BOSS data.

For Case 2, we show the Hubble parameter in the left panel of Fig. 2 where the blue line represents the adjusted parameters using Planck+BAO data and using Planck+BAO+SNeIa+$H_0$ data for the dashed green line. Comparatively to the previous case, we can see that the Planck+BAO line is compatible with $ξ_2 = 0$ and that the inclusion of the low redshift data (SNeIa and $H_0$) suggests a completely negative coupling constant. This apparent disparity in the BOSS measurement and the Hubble parameter calculated using the parameters of Case 2 can be attributed to the best fit value of the cosmological parameters found in [20]. Although $Ω_{DE}$ does not change much from Case 1 to Case 2, the adjusted cosmological parameters are quite different, especially the density parameter of dark matter, namely $Ω_{DM}^0 = 0.240$ and $Ω_{DM}^0 = 0.144$ for Planck+BAO and Planck+BAO+SNeIa+$H_0$ respectively. This is consistent with the fact that $ξ_2 < 0$ in left panel of Fig. 2 where some of the dark matter decayed into dark energy, leaving a smaller dark matter component now. This shows that Model I Case 2 with the cosmological parameters of [20] is not a good candidate to both describe the BOSS data and alleviate the cosmological constant problem.

Using $Ω_{DE}$ from Case 2, we plot the Hubble parameter for the parameters of Table I in the right panel of Fig. 2. The result is very similar to Case 1 in Fig. 1 show-
ing that an interacting model with a positive coupling constant explains the BOSS measurement, rejecting null interaction at 2σ.

Now we turn to the discussion of Model II where the interaction is still proportional to the energy density of dark energy but with ω_{DE} < −1, i.e. with phantom dark energy. Using the best fit cosmological parameters obtained from the Planck+BAO and Planck+BAO+SnIa+H_0 data sets (given in Table XI of [20]), we plot H(2.34) in the left panel of Fig. 3. In the right panel, we plot the same quantity using the cosmological parameters used by BOSS (see Table II). As we can see in the left panel of Fig. 3, the interacting Model II explains the BOSS value of H(2.34) with a positive coupling different from zero by more than 2σ, and by more than 3σ for Planck+BAO+SnIa+H_0. We note that in this case, the necessary value of the coupling constant is much larger than in the previous models. In the right panel, we can see that Model II is still compatible with the Hubble measurement, but with smaller confidence levels than before (2σ for Planck+BAO and a little higher than 1σ for Planck+BAO+SnIa+H_0). Overall, Fig. 3 shows that Model II explains the BOSS observation in a very accurate way and still helps alleviate the coincidence problem since the coupling constant must be positive.

Finally, we consider Model III. We evaluate H(2.34) with respect to the coupling constant ξ_1 using the cosmological parameters from the analysis of Planck+BAO and Planck+BAO+SnIa+H_0 contained in Table XII of [20]. This is plotted in the left panel of Fig. 4. Again, we can see that this model describes the BOSS result very well for a positive coupling constant incompatible with zero at 2σ. Using the cosmological parameters from Table II (plotted in the right panel of Fig. 3), we still have a concordance at about 1.5σ. As in the previous case the positive coupling also meets the requirement to alleviate the coincidence problem with a good precision.

Conclusions.—In this Letter, we explored the consequences of interacting dark energy in light of the recent results by the BOSS experiment. The BOSS data indicate that the Hubble parameter at z = 2.34 is smaller than what one would expect from the standard ΛCDM model, something that cannot be explained by simple dynamical dark energy models such as quintessence. Our results suggest that interacting dark energy can naturally explain the BOSS data without introducing exotic forms of dark energy.

We tested three different phenomenological models of interacting dark energy by computing the value of the Hubble parameter at z = 2.34 for different sets of cosmological parameters. We found that Model I can be in agreement with the BOSS result for specific values of the cosmological parameters, but not for Case 2 of [20], and Models II and III showed to be in good agreement with the observations for a small positive coupling constant at good confidence levels. Furthermore, such a positive coupling constant can help alleviate the cosmological constant problem.

In order to further constrain interacting dark energy models, one could refine the analysis of this work by using more data sets and by combining the BOSS data with other observations. In particular, an analysis using the full DR-11 data, which should be released soon, is the topic of a follow-up paper. Furthermore, the JPAS telescope [20] will be able to reproduce and improve the BAO measurements at high redshifts since this instrument is supposed to be optimized to measure quasars at high redshifts compared to previous experiments [21].

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FIG. 3: Plots of $H(2.34)$ as a function of the coupling $\xi_2$ for Model II. The left panel uses the adjusted parameters from Table XI of [20]. The right panel uses the cosmological parameters found in Table [1]. The dashed gray line and the shaded areas are the same as in Fig. [4].

FIG. 4: Plots of $H(2.34)$ as a function of the coupling $\xi_1$ for Model III. The left panel uses the adjusted parameters from Table XII of [20]. The right panel uses the cosmological parameters found in Table [1]. The dashed gray line and the shaded areas are the same as in Fig. [4].

* Electronic address: eabdalla@usp.br
† Electronic address: rkim@physics.mcgill.ca
‡ Electronic address: wang@b.tsjtu.edu.cn
§ Electronic address: jquintin@physics.mcgill.ca

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