Indications of a Late-Time Interaction in the Dark Sector

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We show that a general late-time interaction between cold dark matter and vacuum energy is favored by current cosmological data sets. We characterize the strength of the coupling by a dimensionless parameter q_V that is free to take different values in four redshift bins from the primordial epoch up to today. This interacting scenario is in agreement with measurements of cosmic microwave background temperature anisotropies from the Planck satellite, supernovae Ia from Union 2.1 and redshift space distortions from a number of surveys, as well as with combinations of these different data sets. Our analysis of the 4-bin interaction shows that a nonzero interaction is likely at late times. We then focus on the case $q_V \neq 0$ in a single low-redshift bin, obtaining a nested one parameter extension of the standard ΛCDM model. We study the Bayesian evidence, with respect to ΛCDM, of this late-time interaction model, finding moderate evidence for an interaction starting at $z = 0.9$, dependent upon the prior range chosen for the interaction strength parameter q_V. For this case the null interaction ($q_V = 0$, i.e., ΛCDM) is excluded at 99% C.L.

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Introduction.—Measurements of anisotropies of the cosmic microwave background (CMB) from experiments including the WMAP [1] and Planck [2] satellites, combined with independent measurements of the cosmic expansion history, such as baryon acoustic oscillations [3], have provided strong support for the standard model of cosmology with dark energy (specifically a cosmological constant, Λ) and cold dark matter (CDM). However, the latest CMB data are in tension with local measurements of the Hubble expansion rate from supernovae Ia [4] and other cosmological observables which point towards a lower growth rate of large-scale structure (LSS), including cluster counts [5,6] and redshift-space distortions (RSDs) from galaxy peculiar velocities [7].

At the present time it remains unclear whether these discrepancies may be due to systematic effects in the different methods used for measurements, or whether they could instead be evidence for deviations from ΛCDM. Massive neutrinos have been proposed to reconcile the CMB with LSS observations [8], but they increase the tension with local measurements of the Hubble rate [9]. Dynamical dark energy can help reconcile the CMB and local Hubble expansion measurements, but does not ease the tension with LSS [2]. However, a coupling between the components of the dark sector can strongly influence the evolution of both the background and perturbations. Models with a constant interaction between cold dark matter and dark energy have already been proposed as one possible solution to solve the tension in the measurements of the Hubble constant from the CMB and supernovae [10].

In this Letter we investigate a minimal extension of the ΛCDM model where dark matter is allowed to interact with vacuum energy, without introducing any additional degrees of freedom. We allow the interaction strength to vary with redshift and show that energy transfer from dark matter to the vacuum can resolve the tension between the CMB and RSD measurements of the growth of LSS, making it consistent to combine these two data sets. We consider only RSD measurements as these probe the gravitational potential in the linear regime and do not depend on nonlinear evolution and the formation of collapsed halos and clusters. Our main result is that a model where an interaction in the dark sector switches on at late times is particularly favored with respect to ΛCDM. Assuming an interaction starting at redshift $z = 0.9$, the null interaction case (i.e., ΛCDM) is excluded at 99% C.L.

Model.—Interacting vacuum models (iVCDMs) allow energy-momentum transfer between CDM and the vacuum [11–16]. The background evolution is encoded in the coupled energy conservation equations

$$\dot{\rho}_c + 3H\rho_c = -Q, \tag{1}$$

$$\dot{V} = Q, \tag{2}$$

for the CDM and vacuum densities, ρ_c and V, the standard conservation equations for baryons, photons, and neutrinos, and the Friedmann equation

$$H^2 = \frac{8\pi G}{3}(\rho_{\rm tot} + V), \tag{3}$$

where $\rho_{\rm tot}$ is the total matter and radiation energy density, H is the expansion rate of the Universe, Q is the interaction term and we assume a spatially flat universe. When there is no interaction ($Q = 0$) we have $8\pi GV = \Lambda$, the cosmological constant, and we recover the standard ΛCDM model.

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TABLE I. Constraints at 68% C.L. on cosmological parameters in the iVCDM model when q_V is allowed to vary in four redshift bins.

	Planck	Planck + SN	Planck + RSD
$100\Omega_b h^2$	2.203 ± 0.029	2.203 ± 0.029	2.217 ± 0.028
$\Omega_c h^2$	< 0.060	$0.049^{+0.018}_{-0.044}$	$0.0918^{+0.026}_{-0.010}$
$100\theta_{\rm MC}$	$1.0463^{+0.0032}_{-0.0024}$	$1.0460^{+0.0023}_{-0.0028}$	$1.04302^{+0.00095}_{-0.00183}$
τ	$0.087^{+0.012}_{-0.014}$	$0.086^{+0.012}_{-0.014}$	$0.086^{+0.012}_{-0.013}$
n_s	0.9597 ± 0.0078	0.9599 ± 0.0078	$0.9638^{+0.0071}_{-0.0078}$
$\ln(10^{10}A_s)$	$3.084^{+0.024}_{-0.026}$	$3.082^{+0.024}_{-0.027}$	3.078 ± 0.024
q_1	$-0.62^{+0.18}_{-0.31}$	$-0.61^{+0.21}_{-0.29}$	> -0.29
q_2	$-0.70^{+0.24}_{-0.33}$	$-0.69^{+0.26}_{-0.31}$	$-0.291^{+0.255}_{-0.098}$
q_3	$-0.76^{+0.37}_{-0.40}$	$-0.80^{+0.36}_{-0.42}$	$-0.49^{+0.28}_{-0.16}$
q_4	> -2.12	$-1.58^{+1.51}_{-0.506}$	$-0.92^{+0.48}_{-0.34}$

In general, the interaction is covariantly represented by a 4-vector Q^μ; if we assume that this is proportional to the four-velocity of CDM ($Q^\mu = Qu^\mu$) then the matter flow remains geodesic ($u^\mu \nabla_\mu u^\nu = 0$) and in the comoving-synchronous gauge the vacuum energy is spatially homogeneous [16]. Hence, the perturbation equations in this gauge are the same as in ΛCDM, with zero effective sound speed [17].

Recent studies of interacting vacuum cosmologies have focused on specific models for the interaction, $Q(z)$ [17–21]. In this Letter we want to consider a general interaction $Q(z)$ in different redshift bins. Thus we take an interaction of the form $Q = -q_V HV$, where $q_V(z)$ is a dimensionless parameter that encodes the strength of the coupling [22]. We require $q_V < 0$ to ensure that the matter density remains non-negative. Note that in our notation a negative q_V implies dark matter decaying into vacuum.

We first consider a model in which $q_V(z)$ is a binned (stepwise-defined) function. We have subdivided the redshift range from last scattering until today into four bins, with $q_V(z) = q_i$ $(i = 1, \ldots, 4)$, i.e., parametrizing our iVCDM model with four parameters. We have chosen to include all the redshifts from the primordial epoch to $z = 2.5$ in a single bin (bin 1), as we have few measurements in that range after the CMB last scattering. The other three bins have been chosen with the aim to be mainly sensitive to supernovae (bin 4, $0 \le z \le 0.3$), to RSDs (bin 3, $0.3 \le z \le 0.9$), and to the farthest supernova observations available (bin 2, $0.9 \le z \le 2.5$).

In light of our results for $q_V(z)$, we then focus on the case of a late-time interaction, with $q_V \neq 0$ in a single low-redshift bin.

Analysis.—We have performed a Bayesian analysis with the Monte Carlo Markov chain code CosmoMC [23,24] and a modified version of the Boltzmann code CAMB [25]. The data sets we have considered to assess the likelihood of the model are CMB measurements from Planck [26] including polarization from WMAP [1], SNIa from the compilation Union2.1 [27], and RSD measurements from a number of surveys [28–33], see Fig. 2. We also considered baryon acoustic oscillations [28,30,34,35] and radio galaxies data [36], finding that the constraints from these data sets are equivalent to those from SN; therefore, their addition to our analysis doesn't change our results. A comprehensive analysis including the effects of these data sets will be presented in a forthcoming paper [37].

In this analysis we have chosen a flat prior $[-10, 0]$ for the q_i parameters since the parameters' magnitude is assumed to be of order one. (We will consider later the effect of a wider logarithmic prior, see Fig. 5 and Ref. [37].)

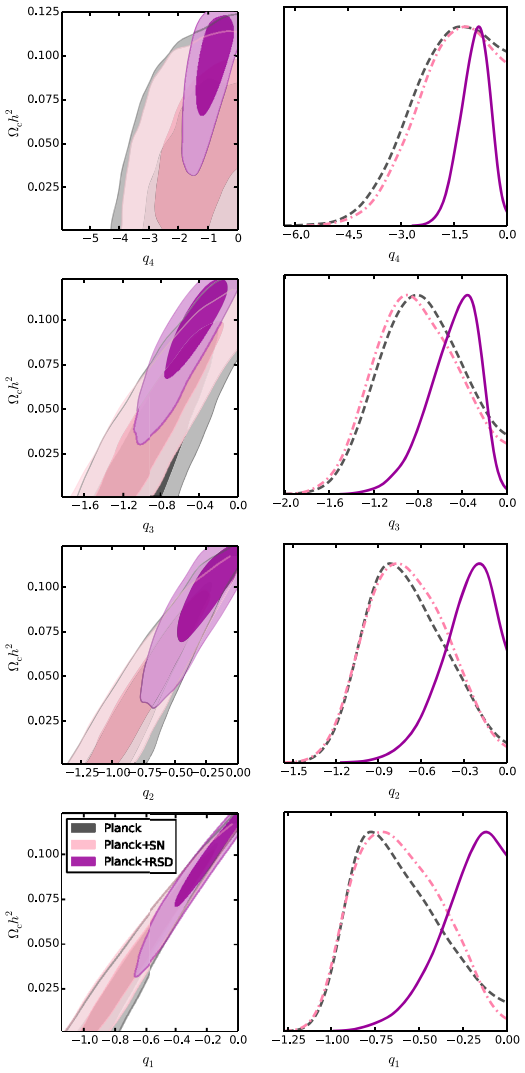

FIG. 1 (color online). Two-dimensional $\Omega_c h^2$-q_i contours at 68% and 95% C.L. (left) and one-dimensional q_i probability distributions (right) from Planck (black), Planck + SN (pink), and Planck + RSD (purple). The addition of the RSD data sets breaks the degeneracy between the two parameters, $\Omega_c h^2$ and q_i, and narrows the probability distributions of q_3 and q_4 in particular. A null interaction at low redshift is excluded with high significance.

TABLE II. Constraints at 68% C.L. on fundamental cosmological parameters for the iVCDM model with $q_V = q_{34}$.

	Best fit	Mean
$100\Omega_b h^2$	2.225	2.216 ± 0.027
$\Omega_c h^2$	0.1170	0.1183 ± 0.0023
$100\theta_{\rm MC}$	1.04150	1.04142 ± 0.00061
τ	0.094	$0.087^{+0.012}_{-0.014}$
n_s	0.9702	$0.9633^{+0.0068}_{-0.0067}$
$\ln(10^{10}A_s)$	3.094	3.080 ± 0.024
q_{34}	−0.128	$-0.156^{+0.068}_{-0.056}$

In the 4-bin interaction case, when considering the CMB only or CMB+SN measurements, the presence of an interaction is allowed but a null interaction is not excluded in any bin (see column 1 and 2 in Table I). This is due to the unbroken degeneracy between the strength of the interaction parameters, q_i, and the present-day CDM density ($\Omega_c h^2$), shown in Fig. 1.

The degeneracy between $\Omega_c h^2$ and the interaction parameters can be broken by the addition of RSD measurements. This imposes a lower limit on the present cold dark matter density and leads to a shift in the posterior distributions for the interaction, as clearly shown in Fig. 1. A null interaction is then excluded at 99% C.L. in bin 3 and at 95% in bin 4, showing that a late-time interaction is preferred by observations (see column 3 in Table I). This result is also supported by a principal component analysis [37].

We note that the iVCDM model can also alleviate the tension that arises in ΛCDM between the Hubble constant measurements from Planck ($H_0 = 67.3 \pm 1.2$) and the Hubble Space Telescope [4] ($H_0 = 73.8 \pm 2.4$). The constraint from Planck in the iVCDM case is $H_0 = 70.4 \pm 2.5$ (see also Ref. [21]). The combination with RSD measurements breaks the degeneracy between q_i and $\Omega_c h^2$, leading to $H_0 = 68.0 \pm 2.3$.

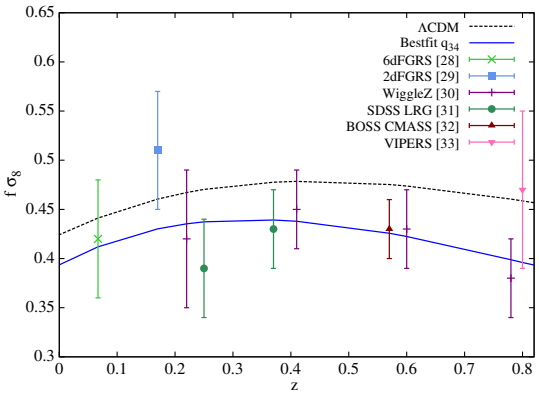

FIG. 2 (color online). RSD measurements [28–33] plotted against the theoretical predictions from the best-fit iVCDM model with $q_{34} = -0.128$ (blue) and a ΛCDM model ($q_{34} = 0$) with the same values of cosmological parameters (black).

TABLE III. Minimum χ^2 values for CMB + RSD data sets fitted to various theoretical models discussed in the text.

	ΛCDM	4 bins	q_{34} only	$q_{34}, z_{\rm in}$	m_νΛCDM
$\chi^2_{\rm min}$	9818	9811	9811	9810	9813

In light of this analysis, we have also explored the viability of a simpler model with an interaction that switches on at low redshift whose strength is encoded in a constant $q_V \neq 0$ for $z < z_{\rm in}$. In particular, based on the preceding results, we have selected as the interaction starting point $z_{\rm in} = 0.9$, i.e., the upper limit of redshift bin 3. For this reason we will refer to it as the q_{34} model. In this case a null interaction is excluded at 99% C.L. Results are shown in Table II and Fig. 2.

As shown in Table III, when we introduce four parameters to determine the interaction strength in 4 redshift bins, we obtain a much better fit to the data with respect to ΛCDM. Remarkably, the q_{34} model with a single interaction parameter can match the best fit of the more complex model with four independent redshift bins. It reproduces the same best-fit χ^2 with three fewer parameters.

An alternative way to compare different models is to compute the Bayesian evidence. Since the q_{34} model is a one-parameter nested extension of ΛCDM, we can simply compute the Bayes factor B_{01}, that represents the ratio of the models' probability, using the Savage-Dickey density ratio formula

$$B_{01} = \left.\frac{P(q_{34}|\text{data, model 1})}{P(q_{34}|\text{model 1})}\right|_{q_{34}=0}, \qquad (4)$$

where q_{34} is the additional parameter and $q_{34} = 0$ is the value of the parameter for which model 0 (ΛCDM) is recovered.

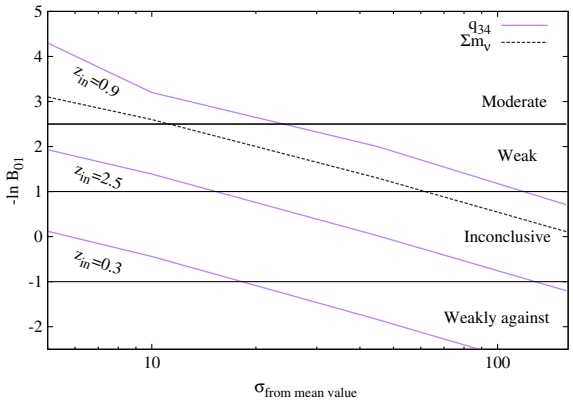

FIG. 3 (color online). Bayesian evidence as a function of the prior width, expressed in terms of standard deviations from the mean value of the nested parameter. In purple (solid line) the q_{34} model ($z_{\rm in}$=0.9) and same model with different choices of $z_{\rm in}$. In grey (dashed line) the m_ν-ΛCDM model. On the right we report the empirical Jeffreys' scale defined in Ref. [39].

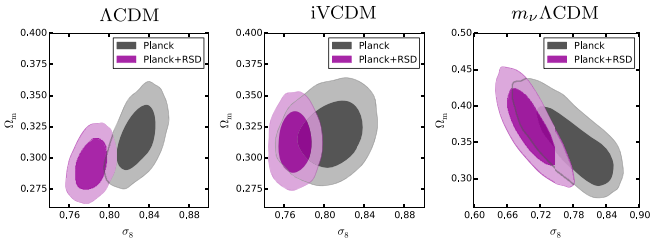

FIG. 4 (color online). Ω_m-σ_8 contours at 68% and 95% C.L. from Planck experiment (black) and Planck + RSD (purple) for three theoretical models. The tension between the Planck and RSD data sets that arises in the ΛCDM model (left) is resolved in the q_{34} interacting vacuum model (middle). Also, in the ΛCDM model with massive neutrinos (right), this tension with RSD is alleviated (in contrast to the tension that arises when considering nonlinear probes of LSS growth [40]).

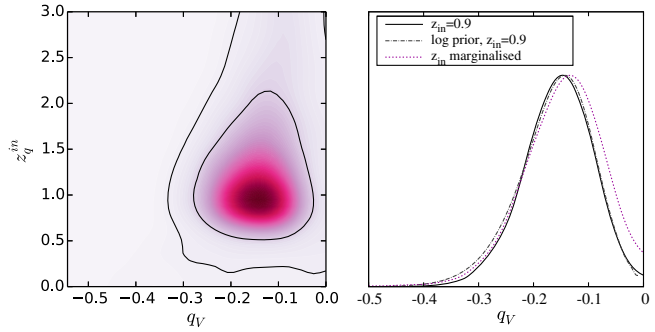

FIG. 5 (color online). Effects of varying $z_{\rm in}$ in the single bin iVCDM model. Left: q_V-$z_{\rm in}$ contours at 68% and 95% C.L.; $z_{\rm in}$ is poorly constrained but the degeneracy with q_V is weak. Right: q_V posterior distribution when $z_{\rm in}$ is either fixed at $z_{\rm in} = 0.9$ (q_{34} model) or marginalized. The posterior when considering a log prior, $\log_{10}|q_V| \in [-2, 2]$ with fixed $z_{\rm in}$ is shown by a dashed line.

The Bayesian evidence for the extended model is $-\ln B_{01}$; thus B_{01} less than one means that the q_{34} model is preferred over ΛCDM.

The Bayesian evidence inevitably depends on the prior distribution of model parameters, decreasing with the prior width. When dealing with phenomenological parameters, such as q_{34}, it is not clear what range for the prior should be considered when computing the evidence [38]. For this reason we have explored in Fig. 3 how the evidence changes with the width of the prior. For comparison we have computed the evidence for three late-time interaction models with different choices for $z_{\rm in}$. We have also evaluated the Bayes factor between ΛCDM and another one parameter extension that alleviates the tension between CMB and RSD measurements, namely, ΛCDM with massive neutrinos [8], see Fig. 4. In this case the nested extra parameter is the sum of the neutrino masses, for which we obtain $\sum m_\nu = 0.53 \pm 0.19$ eV. In the rest of our analysis we use the standard fixed value $\sum m_\nu = 0.06$ eV. We see that the evidence for the q_{34} model with $z_{\rm in} = 0.9$ is always higher than the other one-parameter models we study for a given prior width relative to the standard deviation from the mean. The evidence remains moderate even when allowing a prior range for q_{34} equal to 20 standard deviations from the mean.

Possible biases.—In order to check the robustness of our results we have performed some further analysis [37]. First we have explored a model where $z_{\rm in}$ is free to vary. Table III shows that $z_{\rm in} = 0.9$ is a good approximation of the best-fit point of this extended model, and hence maximizes the Bayesian evidence computed above. Marginalizing over $z_{\rm in}$ slightly broadens and shifts the posterior distribution for q_V, as shown in Fig. 5. We also show in Fig. 5 that choosing a wider logarithmic prior, $\log_{10}|q_{34}| \in [-2, +2]$ for fixed $z_{\rm in}$, has a small effect on the posterior.

Moreover, we have tested our results against variation of the lensing amplitude parameter of the CMB temperature, A_L. In ΛCDM, Planck measurements point towards an A_L value that is higher than the standard value, $A_L = 1$, [2,41] used in the preceding analysis. In our iVCDM model a degeneracy exists between A_L and q_V that reduces the strength of the interaction when A_L increases. However, the indication for an interaction is maintained at 95% C.L.

Finally, given the recent results from the BICEP2 experiment that claim a detection for a tensor to scalar ratio r different from zero [42], we have investigated if our results may be affected. The interaction parameter is actually very poorly degenerate with r and the inclusion of the BICEP2 data set changes the Bayes evidence by only 1%.

Conclusions.—We have shown that an interacting vacuum cosmology, where the strength of the coupling with CDM varies with redshift, is a possible solution to the tension that arises in the standard ΛCDM model between CMB data and LSS linear growth measured by RSD, see Fig. 4. In particular we have found that an interaction which switches on at late times ($z \sim 0.9$) is particularly favored. In this context, we have obtained a very tight constraint on the interaction strength parameter, excluding the ΛCDM model (i.e., a null interaction) at 99% C.L. We have also verified that the probability of late-time interaction is only weakly affected by changes in the value of the tensor-to-scalar ratio or the lensing amplitude parameters.

We have only considered here constraints on the linear growth of LSS, as the nonlinear coupled evolution of interacting vacuum and dark matter has yet to be studied in detail. It will be important to examine the predictions of iVCDM for cluster number counts; this provides tight constraints, e.g., on ΛCDM, but requires nonlinear modeling. Interacting vacuum models can be recast [16] as clustering quintessence with vanishing sound speed [43] and/or irrotational dark matter [44], either of which could have distinctive predictions for nonlinear collapse.

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