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Parameter splitting in dark energy: is dark energy the same in the background and in the cosmic structures?

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Abstract

We perform an empirical consistency test of General Relativity/dark energy by disentangling expansion history and growth of structure constraints. We replace each late-universe parameter that describes the behavior of dark energy with two meta-parameters: one describing geometrical information in cosmological probes, and the other controlling the growth of structure. If the underlying model is correct, that is under the null hypothesis, the two meta-parameters coincide. We present a global analysis using state-of-the-art cosmological data sets which points in the direction that cosmic structures prefer a weaker growth than that inferred by background probes. This result could signify inconsistencies of the model, the necessity of extensions to it or the presence of systematic errors in the data. We examine all these possibilities. The fact that the result is mostly driven by a specific sub-set of galaxy clusters abundance data, points to the need of a better understanding of this probe.

1 Introduction

The ΛCDM model has shown an impressive agreement with the observational data gathered so far. Nevertheless, there are known tension in some parameters among Planck observations and low redshift measurements, such as H_0 and σ_8. In addition, the cosmological constant as a non-varying vacuum energy is highly fine tuned in the absence of a fundamental symmetry that sets the value of this constant to its small observed value. Alternative dynamical models or modifications of the gravitational sector of the theory, have been proposed, but the origin of the cosmic acceleration is still unknown.

We disentangle the expansion history and growth of structures constraints and compare them to test the consistency of General Relativity and try to shed some light in the nature of the cosmic acceleration. Moreover, our procedure allows to detect systematics or tensions among the different data sets. The work and results reported on these Proceedings are collected in a more complete way and with further discussion in Reference [2].

2 Parameter splitting

As first emphasized by [10], in General Relativity (GR) within minimally coupled dark energy models, the expansion history fully determines the growth history. Conversely, if cosmic acceleration is to be explained with modifications of the gravitational sector, the growth history inferred from the expansion history using General Relativity would not necessarily fit the observed growth of cosmic structures. In the pioneering work of Ref. [5] it was proposed using this fact to perform a consistency test of GR/dark energy.

Parameter splitting is a general but powerful technique to check the consistency of a model. Its advantage is that, by offering a null test and resorting to meta-parameters, it is model-independent. We replace each dark energy parameter with two meta-parameters: one constraining the expansion history and the other controlling the growth of structure. If the null test is not failed (the meta-parameters are equal), there is no reason to claim that new physics is needed. On the other hand, if the null test is failed in the absence of systematics, it could be a hint of new physics needed by the standard model of cosmology, or a failure of GR. However, the presence of unaccounted systematic errors can also lead to a failure of the split parameters null test; hence parameter splitting is also sensitive to systematic errors. Nonetheless, by performing the analysis with different, combinations of data sets, it allows us to disentangle systematics from new physics.

Parameter splitting was applied for the first time to the dark energy parameters in [12], where no evidence of deviations from the null hypothesis was found. Recently, Ruiz et al. [9] find a tension of 3.3σ between $w_{\rm geom}$ and $w_{\rm growth}$ when splitting w and $\Omega_{\rm DE}$ simultaneously, mostly driven by Redshift Space Distortions data (RSD). This tension is alleviated when $\sum m_\nu$ is let to vary: however, the recovered $\sum m_\nu$ is too high compared with current upper limits coming from [6, 4].

3 Data and analysis

We separate the cosmological probes depending on whether they are sensitive to the expansion history of the Universe or to structure growth (Table 1). We do not include in this work weak lensing power spectrum measurements because the signal coming from geometry and that coming from growth are intertwined and not easy to separate out.

Table 1: Cosmological probes that we use to constrain either geometry or growth.

Cosmological Probe	Measurement	Geometry	Growth
CMB	high ℓ in TT, TE and EE power spectra	✓	
CMB	low ℓ in TT, TE and EE power spectra		✓
CMB	$40 \leq L \leq 400$ lensing power spectrum		✓
SNeIa	D_L	✓	
BAO	$D_V/r_{\rm s}$, $D_A/r_{\rm s}$ and $c/(Hr_{\rm s})$	✓	
Clusters	$\Omega_{\rm M}^{\beta}\sigma_8$		✓
RSD	$f\sigma_8$		✓

We adopt wCDM model to account for variations in the behavior of dark energy. Thus we consider the following possibilities for splitting dark energy parameters: only w, only $\Omega_{\rm DE}$, or both simultaneously. Therefore, the cosmological parameters in our analysis are:

$$\{\Omega_{\rm b}h^2, \Omega_{\rm CDM}^{\rm geom}h^2, \Omega_{\rm CDM}^{\rm growth}h^2, H_0, A_S, n_s, \tau_{\rm reio}, w_{\rm geom}, w_{\rm growth}\}\,, \tag{1}$$

where when a parameter is not split, we impose both meta-parameters to be equal. We modify CLASS [3] and Monte Python [1] to include the parameter splitting and to compute the expansion history (growth of structure) observables using geometry (growth) meta-parameters.

4 Results with full data set

In the case where the equation of state of dark energy is split, we find no evidence of deviations from the null hypothesis or $w = -1$ (Figure 1 top left). Splitting only $\Omega_{\rm DE}$ (Figure 1 top right) we find a tension of 3.8σ between the two meta-parameters for $\Omega_{\rm DE}$ in the direction of an excess of dark energy only felt by the growth of structures, which suppresses the clustering of large scale structures. If we use the data of Planck 2013 instead of the data of Planck 2015, we find that the disagreement is larger. In this case the tension is $\geq 4\sigma$).

When we split both w and $\Omega_{\rm DE}$ at the same time (Figure 1 bottom) we find that the constraints on $w_{\rm geom}$ and $w_{\rm growth}$ are consistent with the fiducial value $w = -1$ but they present a tension of 3.5σ between them. In the case of $\Omega_{\rm DE}$ meta-parameters, the null hypothesis is excluded at $\geq 4.4\sigma$. Using instead Planck 2013 data, the tension in w disappears. The tension in $\Omega_{\rm DE}$ is also lower in this case, but still very significant, ($\geq 4\sigma$).

The tensions between the meta-parameters might be provoked by any physics beyond the standard cosmological model that affects the growth of structures and expansion history in a different way, such as non standard neutrino properties. We explore whether including extra degrees of freedom in the neutrino sector is favored by the data and thus alleviates the tensions found. When giving freedom to the number of the neutrino species, we do not find any significant difference with respect to the previous findings and any deviation from the standard value of $N_{\rm eff}$. When $\sum m_\nu$ is left as a free parameter, constraints weaken slightly

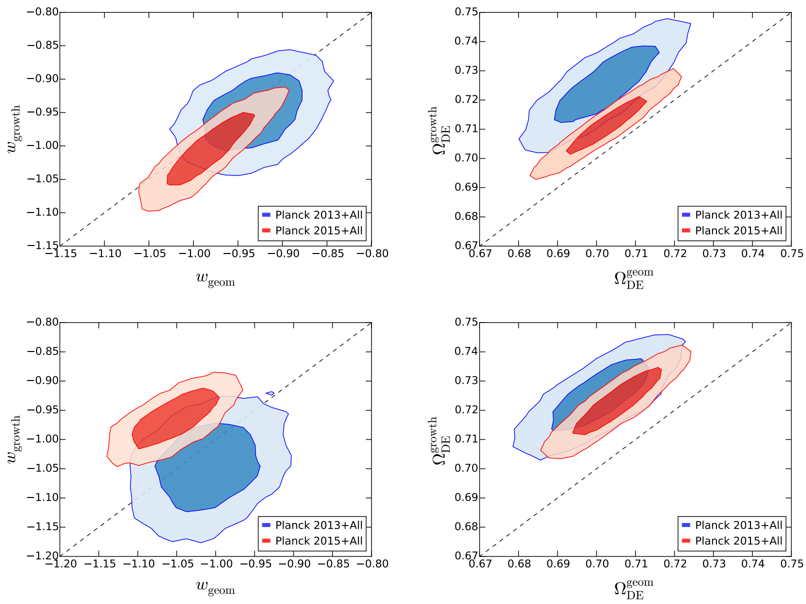

Figure 1: *Top*: Marginalized 68% and 95% confidence level constraints in the $w_{\rm geom}$-$w_{\rm growth}$ plane in the case of only splitting w (left) and in the $\Omega_{\rm DE}^{\rm geom}$-$\Omega_{\rm DE}^{\rm growth}$ plane when splitting only $\Omega_{\rm DE}$ (right). *Bottom*: The same, but when splitting both w and $\Omega_{\rm DE}$

and tensions are reduced but do not disappear. The most reduced is when splitting only in $\Omega_{\rm DE}$: the disagreement is reduced from 3.8 to 2.4σ but $\sum m_\nu = 0.21 \pm 0.10$ eV. This value is too high compared with upper limits from large scale structure observations [6, 4]. Therefore, massive neutrinos can not be the (full) solution to this problem.

5 New physics, inadequacy of the modeling or systematic errors?

Before claiming evidence of deviations from GR within a minimally coupled dark energy, it is necessary to rule out systematics in the data. In principle, parameter splitting offers a powerful tool to test for it. With redundancy, when different data available probing the same quantity (e.g., growth) in the same redshift range and over the same scales, results from different data sets can be compared. This can be used to uncover "the odd one out", likely affected by systematics. With current data redundancy is limited. Yet, here we attempt to test for systematics in this way, even if only as a proof of principle. Tensions are mostly driven by the clusters data set, although for the cases where we split both w and $\Omega_{\rm DE}$, RSD data also contribute (Figure 2 top). If we remove the clusters data of [11, 7] from the analysis, the tensions are considerably reduced (Figure 2 bottom).

6 Comparison with previous works

There are differences between our findings and those of Ruiz et al. [9]. They find a tension in w meta-parameters only when w and $\Omega_{\rm DE}$ are split, mostly driven by RSD data. We find a tension of a similar level in w too. However, in our analysis, it is the $\Omega_{\rm DE}^{\rm growth}$ meta-parameter that is affected most and it is driven by clusters data.

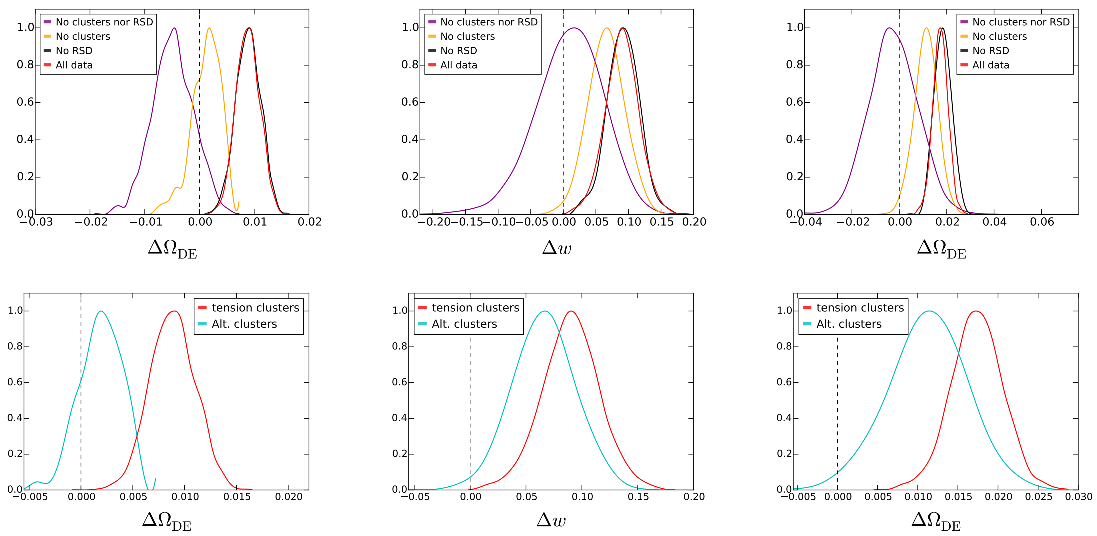

Figure 2: *Top*: Marginalized 68% and 95% confidence level constraints in the $\Omega_{\rm DE}^{\rm geom}$-$\Omega_{\rm DE}^{\rm growth}$ plane and $w_{\rm geom}$ - $w_{\rm growth}$ plane for different data combinations. Left: splitting only $\Omega_{\rm DE}$. Middle and right panels: splitting both w and $\Omega_{\rm DE}$. *Bottom*: The same, using all the data sets (red) and removing [11, 7] from clusters dataset.

Ruiz et al. [9] use priors of the early universe (via the compressed constraints on the CMB peaks positions) and do not include any CMB constraint on growth from the low ℓ or lensing. We use the full Planck likelihood. For that reason, our constraints on $w_{\rm growth}$ from CMB are too tight for RSD data to push it away from the null hypothesis and giving freedom to the neutrino masses does not solve the problem. For cluster data, Ref. [9] uses measurements of [8], which are consistent with ΛCDM and for which we do not find any tension.

7 Conclusions

We have performed an empirical consistency test of GR/dark energy within a wCDM model disentangling expansion history and growth of structures constraints using parameter splitting. This procedure can also be used as a tool to detect systematics or inconsistencies among data sets. In the standard cosmological model that assumes GR, the split parameters have to agree. This is the null hypothesis.

We find significant tensions ($\geq 3.5\sigma$) between the split parameters whenever we split $\Omega_{\rm DE}$. These tensions are only partially alleviated when the sum of neutrino masses is allowed to be a free parameter, but the required value of $\sum m_\nu$ is too high given the current cosmological upper limits. Therefore, non standard neutrino physics is not a solution for the problem

We identify a specific set of measurements of cluster abundances, those obtained by [11] and [7], as the main responsible of the tensions. This leads us to conclude that, before interpreting the tension as a failure of the GR+wCDM model, a better modeling and interpretation of cluster abundance as a probe of the growth of cosmic structures is needed.

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