Cosmological constraints from a joint analysis of cosmic growth and expansion

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ABSTRACT

Combining measurements on the expansion history of the Universe and on the growth rate of cosmic structures is key to discriminate between alternative cosmological frameworks and to test gravity. Recently, Linder (2017) proposed a new diagram to investigate the joint evolutionary track of these two quantities. In this letter, we collect the most recent cosmic growth and expansion rate datasets to provide the state-of-the-art observational constraints on this diagram. By performing a joint statistical analysis of both probes, we test the standard ΛCDM model, confirming a mild tension between cosmic microwave background background predictions from Planck mission and cosmic growth measurements at low redshift \((z < 2)\). Then we test alternative models allowing the variation of one single cosmological parameter at a time. In particular, we find a larger growth index than the one predicted by general relativity \(\gamma = 0.65^{+0.08}_{-0.04}\). However, also a standard model with total neutrino mass of \(0.26 \pm 0.10\) eV provides a similarly accurate description of the current data. By simulating an additional dataset consistent with next-generation dark-energy mission forecasts, we show that growth rate constraints at \(z > 1\) will be crucial to discriminate between alternative models.

Key words: cosmology - observations - cosmological parameters - methods: data analysis

1 INTRODUCTION

Since the discovery of the accelerated expansion of the Universe (Riess et al. 1998; Perlmutter et al. 1999), different cosmological probes have been exploited to constrain the expansion history of the Universe and the growth rate of cosmic structures therein (for a comprehensive review, see e.g. Weinberg et al. 2013). The main quantities to be measured are the Hubble parameter, \(H(z) = \dot{a}/a\), that describes the background expansion, and the linear growth rate \(f(z)\), defined as \(f = d \ln G/d \ln a\), where \(a\) is the scale factor, and \(G\) is the growth factor of the matter density contrast. Usually, the quantity that is actually constrained is \(\sigma_8(z)\), where \(\sigma_8\) is the matter power spectrum normalisation at \(8 \, h^{-1}\)Mpc.

Typically, \(H(z)\) and \(f \sigma_8(z)\) are measured separately using different cosmic probes, whose intrinsic properties make them more sensitive to some parameters, and less to others. For instance, type IA supernovae (SNe) trace luminosity distances up to \(z \sim 1 - 1.5\), cosmic chronometers provide a direct measurement of \(H(z)\) up to \(z \sim 2\), redshift-space distortions constrain \(f \sigma_8(z)\) and baryon acoustic oscillations (BAO) give information on both \(H(z)\) and \(f \sigma_8(z)\), but with less redshift coverage than the other probes. It is a common practice to combine different probes to increase the accuracy on the determination of cosmological parameters, but usually information on the growth factor and expansion are used disjointly (but see e.g. Rapetti et al. 2013). Recently, Linder (2017) proposed a new diagram exploiting these two quantities together. Specifically, it has been shown that in the \(H(z)/H_0\) vs. \(f \sigma_8(z)\) plane different cosmologies can be more easily disentangled.

In this letter, we take advantage of the most recent measurements of both \(H(z)\) and \(f \sigma_8(z)\) to explore the approach suggested by Linder (2017) from an observational perspective. The goal of this work is to collect the most recent observational data to provide the best available constraints on the \(H(z)/H_0\) vs. \(f \sigma_8(z)\) diagram. We used data from cosmic chronometers and redshift-space distortions to constrain possible extensions to the standard flat ΛCDM model and provide forecasts for next-generation galaxy redshift surveys.
Figure 1. The redshift evolution of the Hubble parameter, $H(z)$, (upper panel), and of the linear growth rate, $f\sigma_8(z)$ (lower panel). The grey squares show the data used in this analysis, as described in Section 2. The black points show the binned data used to construct the $H(z)/H_0$-$f\sigma_8(z)$ diagram. Best-fit models to $H(z)$ and $f\sigma_8(z)$ combined are shown with different lines: the dashed grey lines show the reference Planck2016 flat $\Lambda$CDM cosmology, while the coloured ones its extension, with free $\gamma$ (gold), $\Omega_M$ (blue), $\Sigma m_\nu$ (green) and $w_{DE}$ (red). The yellow shaded areas show the 68% confidence levels of the free $\gamma$ model, for illustrative purposes.

2 METHODS AND DATA

To construct the $H(z)/H_0$-$f\sigma_8(z)$ diagram (Linder 2017), we collect the largest homogeneous dataset of $H(z)$ and $f\sigma_8(z)$ measurements, aimed at minimising any possible inconsistencies between different probes.

Differently from previous analyses (e.g. Rapetti et al. 2013) that constrained the expansion history of the Universe based on indirect measurements, such as the luminosity distance $D_L(z)$ from SNe or the acoustic-scale distance ratio $D_V(z)/D_L$ from BAO, here for the first time we rely only on direct constraints on the Hubble parameter $H(z)$ obtained with the cosmic chronometer method. Originally proposed by Jimenez & Loeb (2002), this technique has been widely tested on different galaxy-redshift surveys, providing a direct estimate of $H(z)$ without any cosmological assumption, over a large redshift range ($0 < z < 2$, see Moresco et al. 2016, for a detailed discussion). In this work, we use in particular the measurements provided by Simon et al. (2005); Stern et al. (2010); Moresco et al. (2012); Zhang et al. (2014); Moresco (2015); Moresco et al. (2016); Ratzimbazafy et al. (2017), that are reported in the upper panel of Fig. 1. We note that the cosmic chronometer method is quite new in the panorama of cosmological probes, and hence, while promising, it has not had the time yet to be studied to the same extent of more standard probes, such as BAO and SNe. We refer to Weinberg et al. (2013) for a detailed review and comparison of the strengths and weaknesses of the various probes (see also Guidi et al. 2015; Liu et al. 2016; Goddard et al. 2017, for additional discussions).

For the linear growth rate, we consider the $f\sigma_8(z)$ dataset recently suggested by Nesseris et al. (2017), which collects only the independent measurements provided by Percival et al. (2004); Davis et al. (2011); Hudson & Turnbull (2012); Turnbull et al. (2012); Beutler et al. (2012); Samushia et al. (2012); Blake et al. (2012, 2013); Feix et al. (2015); Howlett et al. (2015); Huterer et al. (2016); Chuang et al. (2016); Okumura et al. (2016); de la Torre et al. (2017). These data are shown in the lower panel of Fig. 1.

We analysed both datasets with a standard $\chi^2$ minimisation approach. As discussed in Moresco et al. (2016) and Nesseris et al. (2017), the covariance matrix is diagonal for almost all measurements considered, except for the WiggleZ $f\sigma_8(z)$ data, for which we used the covariance matrix provided by Blake et al. (2012).

As reference model, we consider the baseline flat $\Lambda$CDM model obtained by Planck Collaboration et al. (2016) (hereafter Planck2016), which assumes two massless and one massive neutrino with mass 0.06 eV, $H_0 = 67.8$ km/s/Mpc, $\Omega_M = 0.308$, $w_{DE} = -1$. We also set the value of the cosmic growth index $\gamma$ to 0.545, as predicted by general relativity, where $f(z) \propto \Omega_m(z)^\gamma$. As already discussed in previous works (e.g. Macaulay et al. 2013; Gil-Marín et al. 2017; Nesseris et al. 2017; Marulli et al. 2017), Planck2016 constraints are in some tension with low-redshift measurements, in particular with $f\sigma_8(z)$ constraints from recent redshift-space distortion analyses. This finding is confirmed also by the present work, as can be noted in the bottom panel of Fig. 1, that shows that Planck predictions overestimate, on average, $f\sigma_8(z)$ measurements at $z < 1$.

We explore four possible extensions to the reference
ΛCDM model in order to get a better fit to the data, by changing each time one single parameter. Specifically, we vary the cosmic growth index $\gamma$, the matter density parameter $\Omega_M$, the total neutrino mass $\Sigma m_\nu$, and the dark-energy equation of state parameter $w_{DE}$. The uncertainties in the current data are still too large to disentangle the degeneracies between the effects produced by some of these parameters, as will be shown in the following Section. Therefore, we decided to explore the effect of changing each parameter singularly.

We consider the following flat priors in the statistical analyses: $\gamma \in [0, 1.5]$, $\Omega_M \in [0.1, 0.6]$, $\Sigma m_\nu \in [0, 1]$ eV, and $w \in [-1, 0.2]$. We note, however, that our results are not affected by the choice of these values, since all our results are well within the considered ranges.

To investigate the sensitivity of our data to the two probes, we perform both a fit separately to $H(z)$ and $f_{\sigma_8}(z)$, and a combined fit. In order to construct the $H(z)/H_0$-$f_{\sigma_8}(z)$ diagram, we bin both datasets in the same redshift ranges chosen to get a uniform redshift sampling, having at least three points in both $H(z)$ and $f_{\sigma_8}(z)$ bins, with the exception of the last two bins, where the sampling in $f_{\sigma_8}(z)$ is very scarce. In each redshift bin we estimate the variance weighted mean values of $H(z)$ and $f_{\sigma_8}(z)$. These data are reported in Fig. 1 as a function of the mean redshift of the bins. This specific procedure is adopted purely for illustrative purposes (see Fig. 2 and 3), while all statistical analyses are performed on the original unbinned datasets.

To estimate $H(z)$ and $f_{\sigma_8}(z)$ in the different cosmological models considered in this work, we exploit the CosmoBolognaLib, a large set of Open Source C++/Python libraries1 (Marulli et al. 2016).

3 ANALYSIS AND DISCUSSION

Fig. 1 compares the best-fit models with the $H(z)$ and $f_{\sigma_8}(z)$ datasets considered in this work. The values of the best-fit parameters of the four models considered, using $H(z)$ and $f_{\sigma_8}(z)$ data both separately and combined together, are reported in Tab. 1. As previously stated, these results have been obtained by allowing the variation of one single parameter at a time. The goal is to quantify how the relaxation of each cosmological parameter can reduce the tension between the data and the reference model. Both the $\gamma$, $\Omega_M$ and $\Sigma m_\nu$ models provide an accurate description of the data, in particular at low redshift ($z < 0.5$). On the contrary, the $w_{DE}$ model does not provide an appreciably better fit, converging both at low and high redshifts to the Planck2016 reference model.

As discussed above, we decided not to include in our datasets measurements of $H(z)$ from other probes, such as from BAO (Chuang & Wang 2012; Blake et al. 2012; Font-Ribera et al. 2014; Delubac et al. 2015), to avoid mixing systematics from different probes that may bias the results. However, we verified that our results when including these data are consistent within 1$\sigma$ with the ones obtained with the dataset considered, except for $w_{DE}$, which results closer to -1 and yet more at odds with lower-redshifts $f_{\sigma_8}(z)$ measurements. We tested also different datasets of $f_{\sigma_8}(z)$ obtained with different techniques (e.g. Pezzotta et al. 2017; Hawken et al. 2017), finding consistent results.

To test the significance of these results, we exploit two different selection model criteria, that is the Akaike Information Criterion (hereafter AIC Akaike 1974) and the Bayesian Information Criterion (hereafter BIC Schwarz 1978). For the first criterion, we use the updated definition by Sugiyura (1978), which includes a correction when $N$ is small (here-

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1 Both the numerical libraries and the datasets analysed in this work are available at the following GitHub repository: https://github.com/federicomarulli/CosmoBolognaLib.
The sixth and the seventh columns show the values of $\Delta AIC_c$ and $\Delta BIC$ when also the simulated data are included.
now significant deviations at low redshifts. In particular, the additional data would allow us to distinguish the effect of γ and Σmν at high significance, as reported in Tab. 1.

4 CONCLUSIONS

In this letter, we exploited the largest homogeneous dataset of H(z) and fδ(z, z) measurements currently available to construct the H(z)/H0-fδ(z, z) diagram, recently introduced by Linder (2017), testing the ACMD model and exploring possible extensions. We compared a reference flat ACMD model with four different extensions, each time varying a single cosmological parameter, namely γ, ΩM, Σmν, and wDE. We find that current low-redshift data appear in some tension with respect to the best-fit model obtained from the latest CMB analysis. Either a model with γ = 0.65±0.05 or with Σmν = 0.26±0.10 provides a better fit to the data at moderate to high statistical relevance, with respect to the reference model. Unfortunately, given the current measurement uncertainties, it is not possible to disentangle between these alternatives (Marulli et al. 2011). We thus simulated six additional H(z) and fδ(z, z) measurements at $z \geq 1$ forecasting future dark-energy missions, such as Euclid and WFIRST, and found that these new data will allow us to distinguish between the models considered in this work with high statistical significance.

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