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# The expansion rate of the intermediate universe in light of Planck

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ABSTRACT

We use cosmology-independent measurements of the expansion history in the redshift range $0.1 \lesssim z < 1.2$ and compare them with the Cosmic Microwave Background-derived expansion history predictions. The motivation is to investigate if the tension between the local (cosmology independent) Hubble constant $H_0$ value and the Planck-derived $H_0$ is also present at other redshifts. We conclude that there is *no tension* between Planck and cosmology independent-measurements of the Hubble parameter $H(z)$ at $0.1 \lesssim z < 1.2$ for the $\Lambda$CDM model (odds of tension are only 1:15, statistically not significant). Considering extensions of the $\Lambda$CDM model does not improve these odds (actually makes them worse), thus favouring the simpler model over its extensions. On the other hand the $H(z)$ data are also not in tension with the local $H_0$ measurements but the combination of all three data-sets shows a highly significant tension (odds ∼1:400). Thus the new data deepen the mystery of the mismatch between Planck and local $H_0$ measurements, and cannot univocally determine whether it is an effect localised at a particular redshift. Having said this, we find that assuming the NGC4258 maser distance as the correct anchor for $H_0$, brings the odds to comfortable values.

Further, using *only* the expansion history measurements we constrain, within the $\Lambda$CDM model, $H_0 = 68.5 \pm 3.5$ and $\Omega_m = 0.32 \pm 0.05$ (at 68% confidence) without relying on any CMB prior. We also address the question of how smooth the expansion history of the Universe is given the cosmology independent data and conclude that there is no evidence for deviations from smoothness on the expansion history, neither variations with time in the value of the equation of state of dark energy.



## 1. Introduction

The recent release of the determination of cosmological parameters from the Planck [1,2] Cosmic Microwave Background (CMB) observations, has shown that for a $\Lambda$CDM model, the extrapolated value at $z = 0$ of the Hubble parameter, $H_0$, is in tension with the one measured locally via astronomical observations of the local distance scale [3,4]. Such a difference could not be explained by cosmic variance in the standard $\Lambda$CDM model [5,6] and would require a highly inhomogeneous Universe. It could be due to unaccounted systematics in the data in either (or both) experiment, or to a failure of the adopted cosmological model to describe nature.

In a previous paper [3] we discussed the importance of local ($z = 0$) measurements in order to assess the consistency of the currently favoured cosmology model: $\Lambda$CDM. Because the CMB mostly probes the Universe at $z \approx 1100$, any cosmological parameter defined at any other redshift is necessarily model-dependent. Therefore, if cosmological parameters can be measured directly, precisely and robustly at other redshifts than $z \approx 1100$, the comparison with the same quantities derived from the CMB using the standard $\Lambda$CDM model can serve as a test of the model itself.

In Ref. [4] we concluded that local measurements of the expansion rate ($H_0$) and of the age of the Universe were in tension (odds 1:53) with the Planck-derived parameters from the CMB within the $\Lambda$CDM model. The tension was driven by $H_0$ and not by the age. With only the data-sets considered there, it was however not possible to determine whether this tension is a signature of systematics in either measurement or new physics: independent data are needed to make further progress.

One way to further investigate this is to "fill the gap" by focusing on $z > 0$ but still $z \ll 1100$. This can be done by using the recent measurements of $H(z)$ between redshift $0.1 \lesssim z < 1.2$ from the cosmic chronometers project [7–11].

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This method adds cosmology-independent measurements of the expansion rate back to when the Universe was only ∼1/3 of its current age (1/3 to the distance of last-scattering), thus significantly increasing the volume surveyed in the Universe to test the CMB-derived cosmology model. The cosmic chronometer method is the only method that provides cosmology-independent, direct measurements of the expansion history of the Universe. In fact, Supernovae data measure the luminosity distance–redshift relation, which is related to an integral of $H(z)$. However the necessary marginalisation over the (unknown) intrinsic magnitude of the standard candles is effectively equivalent to a marginalisation over an overall amplitude i.e., over $H_0$. Baryon acoustic oscillations must rely on the CMB measurement of a standard ruler (the sound horizon at radiation drag) to extract $H(z)$ information from radial clustering; angular clustering yields a combination of the angular diameter distance and the sound horizon at radiation drag and angle averaged clustering yields a combination of angular diameter distance, $H(z)$ and sound horizon. While the CMB determination of the sound horizon is robust e.g., Ref. [12] it is still somewhat model-dependent (e.g., [13–15]). Following Ref. [11] we concentrate on the redshift range $z < 1.2$.

In this paper we explore whether the expansion history at intermediate redshifts shows any signature of possible deviations from the CMB-inferred one. The paper is organised as follows: we first investigate (Section 3), in a mostly parameter-independent way via Gaussian Processes (GP), if the $H(z)$ data show any sign of the expansion not being smooth: we find none. We also find no evidence for variations of the dark energy equation of state parameter (Section 4). We then explore the constraints on the parameters of several cosmological models (the standard $\Lambda$CDM and its popular extensions) using *only* $H(z)$ data and no CMB prior (Section 5). Finally we compute the tension between the $H(z)$ data and the Planck-derived expansion history for different cosmological models (Section 6). We conclude in Section 7.

## 2. The $H(z)$ data for cosmic chronometers

The idea behind the cosmic chronometers approach is to exploit the fact that $H(z) = dt/dz(1+z)$ and that redshifts are easy to measure very accurately from spectroscopic data. The difficult quantity to measure is $dt$: the change in the age of the Universe as a function of redshift. This can be achieved by measuring (relative) ages of galaxies with respect to a fiducial model, thus circumventing the need to compute absolute ages, if one could find a galaxy population that is uniform enough (i.e. standard clocks, or cosmic chronometers). The cosmic chronometers approach relies on the fact that the most massive galaxies contain the oldest stellar populations: have less than 1% of their present stellar mass formed at $z < 1$, have formed their stellar population at high redshift, $z > 2$, and that since that time this population has been evolving passively. The differential ages of these galaxies can therefore be used to estimate the rate of change of the age of the Universe as a function of redshift and therefore $H(z)$ for $z < 2$. See Refs. [7–11] for more details. The $H(z)$ measurements so obtained are cosmology-independent, in the sense that they do not rely on assuming an underlying cosmological model, but rely on stellar population synthesis models to accurately model the effects of time on the integrated spectrum of the stellar population. Here and in what follows we use the expansion history measurements from Refs. [8,9,11] and in particular we start from the compilation reported in http://www.physics-astronomy.unibo.it/en/research/areas/astrophysics/cosmology-with-cosmic-chronometers of [16]. This compilation has data points that cover redshifts as high as $z = 1.8$. Ref. [11] showed that at $z > 1.2$ the dependence on the assumed stellar population model becomes important. Those authors considered two state-of the art models, "BC03" [17] and "MaStro" [18], and we use the "BC03" results for consistency with the other references where only results for this model are provided. A full treatment that marginalises over the model uncertainty will be presented elsewhere, here we only consider $z < 1.2$ (and therefore for the nature of the sample the data point at the highest redshift is at $z = 1.04$). Note that even in this sample there is one point that shows some dependence on the stellar population model, this is the highest redshift one at $z = 1.04$ from Ref. [11]. This dependence is mild: it is 1.6 times the purely statistical error but the final measurement errors include also sources of systematics (not including stellar model-dependence). We therefore increase slightly (20%) the (total) error bars of the point at $z = 1.04$ to encompass the stellar population model uncertainty. With this corrected error-bars the dependence on the stellar population model becomes insignificant and the results reported below do not depend qualitatively on this point.

## 3. Is the expansion history "smooth"?

We start by investigating if there are any signatures of deviation from smoothness using Gaussian Processes (GP) [19,20], which is a non-parametric Bayesian inference formalism. Authors of Ref. [21] have been the first ones to recently use GP on the same dataset to extrapolate the value of the Hubble parameter at $z = 0$ *assuming smoothness* of the expansion history. Here we use GP with a different purpose: to determine, in the least parametric way, if the data show any deviation from smoothness as a function of redshift.

We will not enter into a detailed description of GPs here but instead refer the interested reader to the literature (see e.g., [19,20] for standard references in the field). GP is a stochastic process that considers independent and identically distributed Gaussian measurement errors, the relations or correlations between measurements are defined via a covariance matrix. Using standard Bayesian methodology, the estimation of $H$ at any value of $z$ is determined by a probability distribution (posterior predictive). This results into a fully probabilistic estimation of the expansion history given the measurements. In our application the different $H(z)$ determinations are uncorrelated, therefore the off-diagonal terms of the covariance matrix determine the smoothness of the fitting function. In this approach, the only choice we have to make is the form of the off diagonal terms of the covariance matrix. We have experimented with various choices of the covariance matrix with similar results, but we report here the outcome of employing the most commonly used covariance matrix, the radial exponential:

$$K(z, z') = \sigma^2 \exp\left(-\frac{(z-z')^2}{2l^2}\right), \quad (1)$$

where $z$ and $z'$ are two different $z$ values (i.e., $z \neq z'$) and $l$, $s$ are the latent parameters or hyper-parameters[1] which are determined using $H(z)$ data themselves. Intuitively, $l$ controls the correlation length and therefore the "smoothness" and $\sigma$ controls the importance of the off-diagonal terms compared to the diagonal ones. The bigger the $l$ is, the smoother the predictive function would look. Similarly, the higher the $\sigma$ is the lower the signal-to-noise ratio is. The values of $l$ and $\sigma$ can be obtained using maximum likelihood estimation. Since we are dealing with hyper-parameters and not parameters, we maximise the marginal likelihood (over functions) and not the likelihood directly. Note that this approach is the same as the hierarchical Bayesian one [22]. To do so we calculate the partial derivative of the marginal likelihood with respect to the hyper-parameters and optimise the hyper-parameters using gradient based search [19].

[1] Hyperparameter is a parameter of a prior distribution; the term is used to distinguish them from parameters of the model for the underlying system under analysis.