Testing Low-Redshift Cosmic Acceleration with the Complete Baryon Acoustic Oscillations data collection

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Baryon Acoustic Oscillations (BAO) involves measuring the spatial distribution of galaxies to determine the growth rate of cosmic structure. We derive constraints on cosmological parameters from the complete BAO published measurements that include 333 data points in the effective redshift range $0.106 \leq z \leq 2.36$. The ΛCDM model yields cosmological parameters as follows: $\Omega_m = 0.287 \pm 0.004$, $\Omega_k = 0.712 \pm 0.004$, $H_0 = 68.63 \pm 0.32\,\text{km/sec/Mpc}$. The comoving distance from the BAO data is $r_d = 148.4 \pm 0.59\,\text{Mpc}$. Combining the BAO data with the Cosmic Chronometers (CC) data and the Pantheon Type Ia supernova data sets increases the significance to around 5σ. Therefore, the cosmic acceleration, the dark energy effect and the Hubble constant can be constrained with high level of significance only from late-time data, independently of the Planck measurements.

**Introduction** - The standard model of cosmology, the ΛCDM model, requires a dark energy (DE) component responsible for the observed late-time acceleration of the expansion rate. The tension between the values of the Hubble constant $H_0$ obtained from the late universe measurements [1] and those from the Cosmic Microwave Background (CMB) by Planck Collaboration [2] is larger than 4σ. This tension is one of the biggest challenges in modern cosmology [3–15].

The measurement of the expansion history of the Universe at low redshifts provides observational tests for the dark energy while counting on different types of astrophysical objects and observational techniques. The use of type Ia supernovae (SNe) as standard candles originally established the accelerated expansion and solidified the introduction of the DE [16, 17]. Baryon Acoustic Oscillations (BAO) provide a standard ruler which has been evolving with the Universe since the recombination epoch [18, 19]. The BAO scale at different times is a powerful tool to constrain the cosmological parameters. BAO are present in the distribution of matter, and include measurements at low redshifts using the clustering of galaxies, from the correlation function of the Lyα, in cross correlation with quasar positions and galaxies. Refinements of the Cosmic Acceleration without Supernova and CMB has been studied with different data sets [20, 21]. Here we show that the complete BAO data collection that incorporates 333 measurements, provides a direct independent test for the cosmic acceleration and yields a strong constraint on the Hubble parameter.

**Theoretical Background** - We assume a Friedmann-LeMaitre-Robertson-Walker metric with the scale parameter $a = 1/(1 + z)$, where $z$ is the redshift. The Friedmann equation for ΛCDM background reads:

$$E(z)^2 = \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda,$$

where $\Omega_r$, $\Omega_m$, $\Omega_\Lambda$ and $\Omega_k$ are the fractional densities of radiation, matter, dark energy and the spatial curvature at redshift $z = 0$. The function $E(z)$ is the ratio $H(z)/H_0$, where $H(z):= \dot{a}/a$ is the Hubble parameter at redshift $z$. The radiation density can be computed as: $\Omega_r = 1 - \Omega_m - \Omega_\Lambda - \Omega_k$. In the late universe, at the redshifts probed by BAO, the radiation fraction is very small, while for a flat Universe, $\Omega_k = 0$. For wCDM, the Friedmann equation is generalized to $\Omega_\Lambda \rightarrow \Omega_{DE}(1 + z)^{-3(1+w)}$. The observed tracer redshifts and angles on the sky need to be converted to distances by adopting a fiducial cosmological model, and the analysis measures the ratio of the observed BAO scale to that predicted in the fiducial model.

Studies of the BAO feature in the transverse direction provide a measurement of $D_H(z)/r_d = c/H(z)r_d$, with the comoving angular diameter distance [22, 23]:

$$D_M = \frac{c}{H_0} S_k \left( \int_0^z \frac{dz'}{E(z')} \right),$$

where

$$S_k(\Omega_k) = \begin{cases} \frac{1}{\sqrt{-\Omega_k}} \sin \left( \sqrt{-\Omega_k} x \right) & \text{if } \Omega_k < 0 \\ \Omega_k & \text{if } \Omega_k = 0 \\ \frac{1}{\sqrt{\Omega_k}} \sinh \left( \sqrt{\Omega_k} x \right) & \text{if } \Omega_k > 0. \end{cases}$$

In our database we also use the angular diameter distance $D_A = D_M/(1+z)$ and the $D_V(z)/r_d$, which is a combination of the BAO peak coordinates above:

$$D_V(z) \equiv [zD_H(z)D_M^2(z)]^{1/3},$$

$r_d$ is the sound horizon at the drag epoch and it is discussed in the corresponding section. Finally for very precise âÂIJline-of-sightâÂIJ (or âÂIJradialâÂIJ) observations, BAO can also measure directly the Hubble parameter [24].

**Methodology** - We describe below the observational data sets and the statistical methods that we use to
explore our parameter space. The data set we use include a broad collection of points. The main contribution to our data set comes from the different data releases (DR) of the Sloan Digital Sky Survey (SDSS): SDSS-III DR8 [25], DR9 [26–28], DR11 [29, 30], DR12 [31–35], DR12 [36] (LOWZ and CMASS), DR12 [37] (Fourier-space), DR10 [38] (2PACF), DR12 [39] (2CPAF), DR14 [40, 41] (LRG), DR7 [42–44] (LRG), DR6 and DR7 [45] (LRG), DR12 [46, 47] (RSD), R11 [48] (lowz) and its extension SDSS eBOSS: DR3 [49], DR7 [50, 51] (LRG + 2dFGRS), DR12 [52–54], eBOSS quasars [55, 56], DR16 [57–61] (ELG+LRG), DR14 [62–64] (quasars), DR16 + DR12 [65, 66] (LRG+CC), DR16 [67] (ELG), DR16 [68, 69] (quasars) and the Lye forest quasars: [70, 71] (DR12), [72, 73] (DR14) [74] DR16, [29, 75] (DR11). To these data points, we add the results from the WiggleZ Dark Energy Survey (DES) [76, 77] the DES collaboration [78] and the Dark Energy Camera Legacy Survey (DECaLS) [79] (LRG). Furthermore, we use data from the 6dF Galaxy Survey (6dFGS) [80, 81]. We also used some earlier tables of BAO data to improve our data sets [82–86].

We refer to this data set as BAO. To this, we add data from the cosmic chronometers measurements [87–91] referred here as CC and also the Pantheon catalog of 1048 type Ia supernovae [92] referred here as Pantheon. Consequently, we use different 333 measurements of the BAO and 40 measurements of the Cosmic Chronometers (CC) measured by those surveys.

Fig. 1 summarizes the data set with some Hubble diagrams presentations. The data set include estimations of the Hubble parameter in different redshifts (with and without the multiplication of the sound horizon distance and ratio \( r_d/r_{wid} \)), the angular distances \( D_H, D_M, D_A \) and \( D_V \) with the corresponding ratios. The last part includes the inverse ratio \( r_d/D_V \) and presented in the left lower panel of Fig. 1.

We use a nested sampler as it is implemented within the open-source packaged Polychord [93] with the GetDist package [94] to present the results. The prior we choose is with a uniform distribution, where \( \Omega_m \in [0; 1] \), \( \Omega_\Lambda \in [0; 1 - \Omega_m] \), \( H_0 \in [60; 80] \) and \( r_d \in [145; 155] \). For the two \( wCDM \) we use \( w \in [-1.5; -0.5] \) and the same prior for \( \Omega_m \), while for \( \Omega_\Lambda \) CDM, we use \( \Omega_k \in [-0.1; 0.1] \), \( \Omega_m \in [0.1; 1] \), \( \Omega_\Lambda \in [0; 1] \). The measurement of the Hubble constant yielding \( H_0 = 74.03 \pm 1.42(\text{km/s}/\text{Mpc}) \) at 68% CL by [1] has been incorporated into our analysis as an additional prior.
The standard model - In this model, we vary 5 parameters: \( \{H_0, \Omega_m, \Omega_\Lambda, r_d, r_d/r_{f_{id}}\} \). On Fig. 2 we report the 68% and 95% confidence levels for the posterior distribution of some of the parameters of the standard \( \Lambda \)CDM model. The numerical values are reported in Table I. When the fit is combined with the CC sample and the BAO, the predicted values are constrained dramatically and even using the Reiss 2019 prior for \( H_0 \) doesn’t lead to a significant tension in the Hubble constant. The matter energy density is smaller than the one reported by Planck (\( \Omega_m^{\text{Planck}} = 0.315 \pm 0.007 \) [2]).

Quantitatively, the full data set including BAO, the Pantheon and the CC data increases the significance to around 5\( \sigma \) for a uniform prior of the Hubble constant. Therefore, the cosmic acceleration, the dark energy effect and the Hubble constant can be constrained with high level of significance only from late-time data, independently of the Planck measurements.

The sound horizon - The BAO scale is set by the sound horizon at the drag epoch \( z_d \) when photons and baryons decouple, given by:

\[
r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz
\]

where \( c_s \approx c (3 + 9 \rho_b/(4 \rho_\gamma))^{-0.5} \) is the speed of sound in the baryon-photon fluid with the baryon \( \rho_b(z) \) and the photon \( \rho_\gamma(z) \) densities respectively [95]. The drag epoch corresponds to the time when the baryons decouple from the photons at \( z_d \approx 1020 \). For a flat \( \Lambda \)CDM, the Planck measurements yield \( 147.09 \pm 0.26 \text{Mpc} \) and the WMAP fit gives \( 152.99 \pm 0.97 \text{Mpc} \) [2]. From large-scale structure combined with CC, SNea and 150.0 \( \pm 1.89 \text{Mpc} \) and with the Local \( H_0 \) measurement \( r_d = 143.9 \pm 3.1 \text{Mpc} \) [2]. Final measurements from the completed SDSS lineage of experiments in large-scale structure provide \( r_d = 149.3 \pm 2.8 \text{Mpc} \) [96]. [97] reports \( r_d = 143.9 \pm 3.1 \text{ Mpc} \).

The posterior distribution of the \( r_d \) vs the Hubble parameter is presented on Fig. 3. The fit yields: 150.7 \( \pm 1.89 \text{Mpc} \) for the BAO data set. Adding the CC and the Type Ia supernova give 148.77 \( \pm 0.67 \text{Mpc} \). Assuming the Riess 2019 measurement as a different prior yields: 148.27 \( \pm 0.57 \text{Mpc} \). Our results are close to Planck.

FIG. 2. The posterior distribution for different measurements with the \( \Lambda \)CDM model with 1\( \sigma \) and 2\( \sigma \) level of significance. The data fit for the BAO is in gray, combined with the Type Ia supernova data with the Reiss 2019 prior is in green. The Pantheon Type Ia supernova is much wider than the complete BAO data fit. The right panel presents the posterior for the dark matter ratio vs. the Hubble constant. The distribution of the Pantheon Type Ia supernova is much wider than the complete BAO data fit.

FIG. 3. The posterior distribution of the sound horizon distance \( r_d \) vs. the Hubble parameter \( H_0 \) with 1\( \sigma \) and 2\( \sigma \) level of significance. The data fit for the BAO is in gray, combined with the Type Ia supernova and the Cosmic Chronometers is in red for a uniform prior and in blue with the Reiss 2019 measurement as a Gaussian prior.
results and those of the SDSS experiments and also to earlier works taking into account only BAO data points [85].

Extensions - We examine two types of extensions of the standard ΛCDM model, the results for which can be seen on Fig. 4 and the values can be found in Table I.

ΩkΛCDM: For all the 3 samples we get a negative spatial curvature (Ωk < 0). This in line with previous results obtained by the Planck 2018 collaboration [2] which found a preference for a closed universe at 3.4σ and also with those obtained by [98] which included the data from CC, Pantheon and a smaller part of the BAO measurements to conclude also negative Ωk for relieving the H0-tension. Under the priors we use and with the larger BAO data set, we do not observe the described tension between Planck and BAO data [99].

The wCDM model - The dark energy equation of state we obtain differs from the one obtained by the Planck collaboration 2018 [2] which find it essentially consistent with a cosmological constant. In our case, it is much closer to the analysis done in [20].

To compare both models to ΛCDM we take into account that both of them represent nested models with 1 degree of freedom difference, on which we can use standard statistical tests like the likelihood ratio test and the Cohen effect size. For the ΩkΛCDM, we get for

| Model        | Parameters | BAO      | Full     | Full + R19     |
|--------------|------------|----------|----------|---------------|
|               | H0[km/s/Mpc]| 67.59 ± 0.86 | 68.42 ± 0.37 | 68.72 ± 0.36 |
| ΛCDM         | Ωm        | 0.293 ± 0.005 | 0.289 ± 0.004 | 0.287 ± 0.003 |
| ΛCDM         | ΩΛ        | 0.708 ± 0.004 | 0.711 ± 0.004 | 0.713 ± 0.003 |
|               | rd [Mpc]   | 150.33 ± 1.89 | 148.78 ± 0.67 | 148.28 ± 0.57 |
| ΩkΛCDM       | Ωm        | 0.440 ± 0.019 | 0.398 ± 0.015 | 0.393 ± 0.015 |
| ΩkΛCDM       | ΩΛ        | 0.658 ± 0.014 | 0.685 ± 0.012 | 0.691 ± 0.014 |
|               | rd [Mpc]   | 148.29 ± 1.21 | 148.17 ± 0.58 | 147.63 ± 0.63 |
|               | Ωk        | −0.055 ± 0.020 | −0.051 ± 0.019 | −0.053 ± 0.022 |
| wCDM         | H0[km/s/Mpc]| 65.82 ± 0.59 | 67.32 ± 0.41 | 67.59 ± 0.38 |
| wCDM         | Ωm        | 0.238 ± 0.025 | 0.269 ± 0.006 | 0.269 ± 0.006 |
| wCDM         | ΩΛ        | 0.755 ± 0.020 | 0.729 ± 0.006 | 0.729 ± 0.006 |
|               | rd [Mpc]   | 148.91 ± 1.24 | 148.73 ± 0.63 | 148.48 ± 0.64 |
|               | w         | −1.257 ± 0.038 | −1.127 ± 0.020 | −1.114 ± 0.018 |
all the 3 models, $p$—values of $p < 10^{-10}$, meaning that they are significant and seem to describe the data better than $\Lambda$CDM. If we use the Cohen’s effect size measure on them, however, we obtain $w = 0.19$, which represents a small to medium effect size. For the wCDM model, the likelihood test leads to $p < 10^{-4}$ with Cohen effect size $w \sim 0.11$, representing a small effect. It is interesting to note that in both cases, the BAO data alone gives above medium Cohen effect sizes. We can conclude that in both cases, for the full data sets, even if there is some observed significance to the proposed extension, the effect size seems small and the $\Lambda$CDM model remains the best fit of the data.

**Discussion** - This work uses the largest collection of BAO data points (333 points) to put constraint on some cosmological parameters. For the full data set including the BAO, the CC and the Pantheon data sets the significance of the derived parameters is around $5\sigma$.

A tension between two fitted parameters is defined as: $T = |A - B|/\sqrt{\sigma^2_A + \sigma^2_B}$, where $A$, $B$ are the mean and the variance of the parameters $A$ and $B$. Using this formula, we find that the tension between the Planck measurements still exist: $2\sigma$ for the $H_0$, 3.6$\sigma$ for the $\Omega_m$, and 1.9$\sigma$ for $r_d$. Therefore, while our results suggest that cosmic acceleration can be deduced only from late time measurements, the tension with Planck values suggests a possibility for new physics [100–120].

**Acknowledgments** - We thank to Sunny Vagnozzi, Eduardo Guendelman, Elhora Di Valentino and Horst Stocker for simulated discussions. D.B. gratefully acknowledge the support from European COST actions CA15117 and CA18108.

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