BAO signatures in the 2-point angular correlations and the Hubble tension

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Abstract An observational tension on estimates of the Hubble parameter, H_0 , using early and late Universe information, is being of intense discussion in the literature. Additionally, it is of great importance to measure H_0 independently of CMB data and local distance ladder method. In this sense, we analyze 15 measurements of the transversal BAO scale, θ_{BAO} , obtained in a weakly model-dependent approach, in combination with other data sets obtained in a model-independent way, namely, Big Bang Nucleosynthesis (BBN) information, 6 gravitationally lensed quasars with measured time delays by the H0LiCOW team, and measures of cosmic chronometers (CC). We find $H_0 = 74.88^{+1.9}_{-2.1} \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $H_0 = 72.06^{+1.2}_{-1.3} \text{ km s}^{-1} \text{ Mpc}^{-1}$ from $\theta_{\text{BAO}}+\text{BBN}+\text{H0LiCOW}$ and $\theta_{\text{BAO}}+\text{BBN}+\text{CC}$, respectively, in fully accordance with local measurements. Moreover, we estimate the sound horizon at drag epoch, r_d , independent of CMB data, and find $r_d = 144.1^{+5.3}_{-5.5} \text{ Mpc}$ (from $\theta_{\text{BAO}}+\text{BBN}+\text{H0LiCOW}$) and $r_d = 150.4^{+2.7}_{-3.3} \text{ Mpc}$ (from $\theta_{\text{BAO}}+\text{BBN}+\text{CC}$). In a second round of analysis, we test how the presence of a possible spatial curvature, Ω_k , can influence the main results. We compare our constraints on H_0 and r_d with other reported values. Our results show that it is possible to use a robust compilation of transversal BAO data, θ_{BAO} , jointly with other model-independent measurements, in such a way that the tension on the Hubble parameter can be alleviated.

1 Introduction

The standard cosmological model, the flat ΛCDM , based on general relativity theory plus a positive cosmological constant and dark matter, has been able to explain accurately the most diverse observations made in the past two decades.

Despite that, as new astronomical observations improve, in precision and in the diversity of cosmic tracers, arises a possible inability to explain within the standard paradigm quantitatively different measurements, and this is putting the ΛCDM cosmology in a crossroads. The most notable issue is the current tension on the Hubble parameter H_0 . Assuming the ΛCDM scenario, Planck-CMB data analysis provides $H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [1], while a model-independent local measurement from Hubble Space Telescope observations of 70 long-period Cepheids in the Large Magellanic Cloud results $H_0 = 74.03 \pm 1.42 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [2]. These estimates are in 4.4σ tension. Additionally, a combination of time-delay cosmography from H0LiCOW lenses and the distance ladder results is at 5.2σ tension with CMB constraints [3]. Another accurate independent measure was carried out in [4], from Tip of the Red Giant Branch, showing $H_0 = 69.8 \pm 1.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Other recent analysis also put in crisis the ΛCDM model [5–10]. In addition to this disagreement with diverse observations, it is important to remember that the cosmological constant suffers from some theoretical problems [11, 12] that motivates alternative scenarios that could, at the same time, explain the observational data and have some theoretical appeal. This stimulated recent discussions about whether a new physics beyond the standard cosmological model can solve the H_0 tension [13–28].

Other less noticed – but not less important – issue concerns the standard ruler measurement, that is, the co-moving sound horizon scale at the end of drag epoch, $r_{\text{drag}} = r_d$. Assuming the flat ΛCDM cosmology, analyses of the CMB measurements from the Planck collaboration [1] and the WMAP team [29] give $r_d = 147.09 \pm 0.26 \text{ Mpc}$ and $r_d = 152.99 \pm 0.97 \text{ Mpc}$ ¹, respectively. But there are also estimates of the sound horizon scale at low redshift combining data from large-scale structure: $r_d = 150.0 \pm 4.7 \text{ Mpc}$ (CSB), $r_d = 143.9 \pm 3.1$

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Mpc (CSBH), where C-S-B-H indicate a combination of data from Cosmic Chronometers, SNe, BAO data, and local H_0 measurement (for details, see [30]). An interesting information regarding the estimate of r_d using CMB data is that this derivation can be somehow biased by model hypotheses [31]. For this, the literature exhibits the efforts to obtain a model-independent estimate of r_d [30,32]. An estimate of this type obtains $r_d = 136.7 \pm 4.1$ Mpc [32], which is in tension of $\sim 2.5\sigma$ and $\sim 3.8\sigma$ with the Planck and WMAP values, respectively (for other analyses see, e.g., [31,33,34]). Recently, final measurements from the completed SDSS lineage of experiments in large-scale structure provide $r_d = 149.3 \pm 2.8$ Mpc [35], in good agreement with Planck-CMB estimate.

The main aim of this work is to obtain constraints on some cosmological parameters of interest in current literature, namely H_0 and r_d , independent of CMB and local distance ladder data, using sets of data obtained following weakly model-dependent or model-independent approaches. Our analyses are done in Λ CDM/o Λ CDM models for comparison because the H_0 tension reported in the literature has been obtained within these models. Such analyses are important, and of great interest, providing an alternative way to investigate the current observational tension on these parameters and whose results can shed light on this problem. To achieve these objectives, in this work we use measurements of the transversal BAO scale (θ_{BAO}), data obtained following an approach that weakly depends on the assumption of a cosmological model, as described in ref. [36] (all these measurements were obtained following the same methodological approach, however, since the clustering analyses were performed with diverse cosmological tracers—blue galaxies, luminous red galaxies, quasars—one should be careful with the systematics of each dataset [for some tests to deal with systematics in data analyses see, e.g.,] [37–39]). A distinctive feature of these data is that they were measured without assuming a geometry of the Universe; this is a crucial advantage as compared with data sets obtained under the hypothesis of a flat geometry, an attribute that may bias cosmological parameter analyses.

For recent discussions on the cosmological constraints investigations under the perspective of BAO measurements by other groups see, e.g., [40–43].

In these combined analyses we also use the big bang nucleosynthesis (BBN) data, information from gravitationally lensed quasars with measured time delays (H0LiCOW data), and the cosmic chronometers (CC) data. We found that a robust analysis from these data sets is possible to get an accuracy up to $\sim 1.7\%$ on H_0 , and this parameter lives in the range to be compatible with local measurements of H_0 . To the authors' knowledge, this is the first H_0 measurement using BAO data information plus others data sets obtained in a weakly model-dependent way, able to gener-

ate high H_0 values, in order to be compatible with local and model-independent measures, within the Λ CDM framework.

The paper is structured as follows. In the next section we present the data sets used in this work and the statistical methodology. In Sect. 3 we discussed the main results of our analysis. In Sect. 4 we outline our final considerations and perspectives.

2 Methodology

We describe below the observational data sets and the statistical methods that we use to explore our parameter space.

Transversal BAO: Let us adopt 15 BAO measurements, $\theta_{\text{BAO}}(z)$, obtained in a weakly model-dependent approach, compiled in Table I in [34]. These measurements were obtained using public data releases (DR) of the Sloan Digital Sky Survey (SDSS), namely: DR7, DR10, DR11, DR12, DR12Q (quasars) [44]. It is important to notice that due to the cosmological-independent methodology used to perform these transversal BAO measurements their errors are larger than the errors obtained using a fiducial cosmology approach. The reason for this fact is that, while in the former methodology the error is given by the measure of how large is the BAO bump, in the latter approach the model-dependent best-fit of the BAO signal quantifies a smaller error. Typically, in the former methodology the error can be of the order of $\sim 10\%$, but in some cases it can arrive to 18%, and in the later approach it is of the order of few percent [36].

Another important feature of these transversal BAO data is that the data points are not correlated. In fact, the methodology adopted to perform these measurements excluded the possibility for covariance between data points because the analyses of the 2-point angular correlation function were done with cosmic objects belonging to disjoint redshift bins (i.e., bins that are not overlapped and moreover separated by a minimum δ_z , separation that excludes the possibility that errors in the redshifts could put one cosmic object in a contiguous bin).

BBN: The deuterium abundance and the radiative capture of protons on deuterium to produce $3He$ is one the most widely used primordial elements for constraining the baryon density. The empirical value for the reaction rate is computed in [45], constraining the baryon density to $100 \Omega_b h^2 = 2.235 \pm 0.016$, where the dimensionless parameter $h \equiv H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$ is the reduced Hubble constant. We adopt this value of $100 \Omega_b h^2$ as a Gaussian prior likelihood in our analyses.

H0LiCOW: A powerful geometric method to measure H_0 is offered by the gravitational lensing. The time delay between multiple images, produced by a massive object (lens) and the

Fig. 1 Left panel: The 68% CL and 95% CL regions in the $H_0 - \Omega_m$ plane, inferred from $\theta_{BAO} + BBN$ analyses in combination with H0LiCOW and CC data. The vertical light-purple and light-red bands correspond to H_0 from BAO + BBN taken from [54] and the SHOES

measurement [2], respectively. Right panel: The 68% CL and 95% CL regions in the $H_0 - r_d$ plane from $\theta_{BAO} + BBN + H0LiCOW$ and $\theta_{BAO} + BBN + CC$ analyses. The parameter H_0 is measured in units of $\text{km s}^{-1} \text{Mpc}^{-1}$ and r_d in Mpc

gravitational potential between a light-emitting source and an observer, can be measured by looking for flux variations that correspond to the same source event. This time delay depends on the mass distribution along the line of sight and in the lensing object, and it represents a complementary and independent approach with respect to the CMB and the distance ladder. Due to their variability and brightness, lensed quasars have been widely used to determine H_0 (see, e.g., [46–48] and references therein). The time delay is highly sensitive to H_0 , but with a weak dependence on other cosmological parameters. In the present work, we use the six systems of strongly lensed quasars reported by the H0LiCOW Collaboration [3], its time delay distances, to constraint directly all free parameters in our baseline.

CC: The late expansion history of the Universe can be studied in a model-independent fashion by measuring the age difference of cosmic chronometers (CC), such as old and passively evolving galaxies that act as standard clocks [49, 50]. In our analysis we consider the measurements of CC as presented in [50].

We ran CLASS+MontePython code [51–53] using Metropolis-Hastings mode to derive constraints on cosmological parameters from the BAO+BBN, BAO+BBN+H0LiCOW and BAO+BBN+CC data combination. Our baseline parameters are $100\omega_b \in [0.8, 2.4]$, $\omega_{cdm} \in [0.01, 0.99]$, $H_0 \in [10, 100]$, and $\Omega_k \in [-1, 1]$. The parameters $\omega_b \equiv \Omega_b h^2$ and $\omega_{cdm} \equiv \Omega_{cdm} h^2$ are the baryon and the cold dark matter energy densities, respectively. The parameter H_0 is the Hubble constant and Ω_k the spatial curvature.

In a first round of analysis we consider that the background expansion framework is fix assuming a flat- Λ CDM scenario. Next, we also analyze the case Λ CDM + Ω_k . All of our runs reached a Gelman-Rubin convergence criterion of $R - 1 < 10^{-3}$. In what follows, we discuss the main results of our analyses.

3 Results

The left panel of Fig. 1 shows the parametric space in the plane $H_0 - \Omega_m$ from $\theta_{BAO}+BBN$, $\theta_{BAO}+BBN+H0LiCOW$ and $\theta_{BAO}+BBN+CC$ data combination. We find $H_0 = 74.88^{+1.9}_{-2.1} \text{ km s}^{-1} \text{Mpc}^{-1}$ and $H_0 = 72.06^{+1.2}_{-1.3} \text{ km s}^{-1} \text{Mpc}^{-1}$ at 68% confidence level (CL) from $\theta_{BAO}+BBN+H0LiCOW$ and $\theta_{BAO}+BBN+CC$, respectively. The total matter density (baryon + dark matter density) is fit to be $\Omega_m = 0.2763^{+0.027}_{-0.028}$ and $\Omega_m = 0.2515^{+0.016}_{-0.016}$ at 68% CL from $\theta_{BAO}+BBN+H0LiCOW$ and $\theta_{BAO}+BBN+CC$, respectively. Since the measurements of θ_{BAO} have error bars a bit larger than other BAO data compilations, one can notice that the H_0 parameter becomes more degenerate from $\theta_{BAO} + BBN$ constraints when compared to other BAO + BBN analyses performed in the literature [54, 55]. Interesting to note that the $H_0 - \Omega_m$ plane, from θ_{BAO} data, also tends to be positively correlated, but generating high H_0 values. We add H0LiCOW lenses and CC data to better bounds the parameter space. In the Appendix we show the consistency between these data sets. In Fig. 1, the horizontal light purple and light red bands correspond to H_0 values from the BAO +

BBN analysis [54] and the SHOES measurement [2], respectively. We note that H_0 is at $\sim 2\sigma$ and $\sim 2.5\sigma$ tension from $\theta_{BAO} + \text{BBN} + \text{H0LiCOW}$ and $\theta_{BAO} + \text{BBN} + \text{CC}$, respectively, when compared to the measurements performed in [54]. In contrast, our H_0 estimates are in agreement with SHOES [2].

Therefore, combining θ_{BAO} with other data obtained in a model-independent way, and without using CMB and supernovae data, we see their concordance with local measurements of H_0 . A direct interpretation of why the ΛCDM scenario is generating high H_0 values, is because our global fit predicts less dark matter today –in contrast, more dark energy– via the relation $\Omega_m + \Omega_{DE} = 1$, where $\Omega_m = \Omega_b + \Omega_{DM}$. Notice that Ω_b here is determined from BBN information. So, the change on Ω_m estimate is due to dark matter density only, once the radiation (photons + neutrinos) contribution is negligible at low- z . Because our joint analysis predicts more dark energy at late times, the Universe expands faster, generating a larger $H(z)$ evolution and high H_0 values. In [34], was analyzed CMB + θ_{BAO} , where we report $H_0 = 69.23 \pm 0.50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, where we can see a displacement of $\sim +2 \text{ km s}^{-1} \text{ Mpc}^{-1}$, in relation to the Planck + BAO analysis made by the Planck Collaboration [1]. Again, it is clear that θ_{BAO} tends to generate higher H_0 values in comparison with other BAO compilation in literature. The H_0 value from CMB data is inferred analyzing the first acoustic peak position, which depends on the angular scale $\theta_* = d_s^*/D_A^*$, where d_s^* is the sound horizon at decoupling (the distance a sound wave traveled from the big bang to the epoch of the CMB-baryons decoupling) and D_A^* is the angular diameter distance at decoupling, which in turn depends on the expansion history, $H(z)$, after decoupling, controlled also by the ratio Ω_{DM}/Ω_{DE} and H_0 mainly. Our joint fit is generating a larger $H(z)$ and, at the same time, changing the slope of the Sachs-Wolfe plateau, that is, the late-time integrated Sachs-Wolfe effect (ISW). Thus, our joint fit (CMB + θ_{BAO}) is changing primarily the D_A^* history, increasing the angular diameter distance to the last scattering surface, thus generating high estimates on the H_0 parameter.

Figure 2 shows a compilation of H_0 measurements taken from the recent literature for direct comparison with our results. We can notice that H_0 obtained in this work is in agreement with SHOES, H0LiCOW+STRIDES and CCHP. Our estimates start to have a significant tension when compared to measures involving other BAO data compilation and Planck data only.

The right panel of Fig. 1 shows the parametric space in the $H_0 - r_d$ plane. We find $r_d = 144.1^{+5.3}_{-5.5} \text{ Mpc}$ (from $\theta_{BAO} + \text{BBN} + \text{H0LiCOW}$) and $r_d = 150.4^{+2.7}_{-3.3} \text{ Mpc}$ (from $\theta_{BAO} + \text{BBN} + \text{CC}$) at 68% CL. Both measures are compatible with each other. This fit represents an r_d constraint obtained independently of CMB data. For a qualitative comparison, the Planck team reported the value $r_d = 147.21 \pm 0.23 \text{ Mpc}$

Fig. 2 Compilation of H_0 measurements taken from recent literature, namely, from Planck collaboration (Planck) [1], Dark Energy Survey Year 1 Results (DES+BAO+BBN) [57], the final data release of the BOSS data (BOSS Full-Shape+BAO+BBN) [56], The Carnegie-Chicago Hubble Program (CCHP) [4], H0LiCOW collaboration (H0LiCOW+STRIDES) [3], SHOES [2], in direct comparison with the H_0 constraints obtained in this work from $\theta_{BAO} + \text{BBN} + \text{H0LiCOW}$ and $\theta_{BAO} + \text{BBN} + \text{CC}$ analyses within the flat- ΛCDM scenario

from CMB + BAO joint analysis. We see that this estimate is in concordance with ours. Regarding analyses independent of the CMB data, we can mention, for instance, a model-independent reconstruction of $H(z)$ done in ref. [58], where it is reported $r_d = 148.48^{+3.73}_{-3.74} \pm 0.23 \text{ Mpc}$. In ref. [59], the sound horizon at radiation drag is considered as a standard ruler, and it is found $r_d = 142.8 \pm 3.7 \text{ Mpc}$. Also, in ref. [30] the authors found $r_d = 143.9 \pm 3.1 \text{ Mpc}$ using CC, SNe Ia, BAO, and a local measurement of H_0 . Using the inverse distance ladder method, the DES collaboration found $r_d = 145.2 \pm 18.5 \text{ Mpc}$ from SNe Ia and BAO measurements [60]. Our estimates are consistent with these measurements too. We note that only the r_d from $\theta_{BAO} + \text{BBN} + \text{CC}$ joint analysis is in $\sim 1\sigma$ tension with ref. [30]. Other results independent of CMB data were obtained in [61–63].

3.1 Adding spatial curvature

Until now we have performed statistical analyses considering the flat ΛCDM model. Here we extend the parameter space to analyse these important quantities, H_0 and r_d , within a model

Fig. 3 Left Panel: The 68% CL and 95% CL regions in the $H_0 - \Omega_k$ plane inferred from $\theta_{BAO} + BBN$ analyses in combination with H0LiCOW and CC data. Right Panel: Parametric space in the $H_0 - r_d$

plane from the analyses with and without the Ω_k parameter. The H_0 parameter is measured in units of km s⁻¹ Mpc⁻¹ and r_d in Mpc

beyond the flat Λ CDM. For this, we now consider the spatial curvature as a free parameter, i.e., $\Omega_k \neq 0$. As we shall see below, our analyses show compatibility with $\Omega_k = 0$, within 1σ error, although we observe an enlargement of the error bars (as expected because there is one more parameter in the analysis).

Analyzing Λ CDM + Ω_k from BAO+BBN+H0LiCOW we find: $H_0 = 75.08^{+3.5}_{-3.0}$ km s⁻¹ Mpc⁻¹ and $\Omega_k = -0.0697^{+0.14}_{-0.26}$. As argued in [3], the time delay is highly sensitive to H_0 , but with a weak dependence on other parameters. Thus, we can note that when assuming Ω_k as a free parameter, and considering the H0LiCOW sample, no significant changes are observed in the baseline of parameters. Only the effect of slightly increasing the error bars due to the presence of an extra parameter, Ω_k . This scenario can change the perspectives when considering BAO+BBN+CC; in fact, in this case we find $H_0 = 66.54 \pm 3.76$ km s⁻¹ Mpc⁻¹ and $\Omega_k = 0.2764^{+0.17}_{-0.28}$. In this case, considering Ω_k as a free parameter, this can significantly change the evolution of the $H(z)$ function, which depends directly on all physical species and geometrical effects. We note this effect by observing an enlargement and shift in the estimate and error bar of H_0 to accommodate Ω_k effects into the $H(z)$ function. In this particular case we find $\Omega_m = 0.2378^{+0.02}_{-0.019}$. Thus, to accommodate Ω_k effects, looking through the relationship $\Omega_k + \Omega_m + \Omega_\Lambda = 1$, and using for comparison the Ω_m best fit derived in the previous section without Ω_k , we note that the presence of Ω_k decreases mainly the value of Ω_Λ . The left panel in Fig. 3 shows the constraints in the plane $H_0 - \Omega_k$. We did not find significant deviations from the $\Omega_k = 0$ case. The

curvature parameter Ω_k have been discussed through other observations recently in [64–68].

The right panel of Fig. 3 shows the 68% CL and 95% CL regions in the $H_0 - r_d$ plane, analyses done with and without the parameter Ω_k for comparison. Assuming Λ CDM + Ω_k , we find $r_d = 146.9^{+4.2}_{-5.7}$ Mpc (from BAO+BBN+H0LiCOW) and $r_d = 158.3^{+5.8}_{-7.1}$ Mpc (from BAO+BBN+CC). As previously commented, in the BAO+BBN+H0LiCOW joint analyses no significant deviations were observed, as compared to the flat case. In the BAO+BBN+CC analyses, we can clearly notice an enlargement for higher values in r_d , possibly due to the change in H_0 and the strong correlation of r_d with H_0 . It is important to emphasize that all analyses investigated here agree with each other.

3.2 SDSS final release

During the final stage of preparation of this work, the SDSS collaboration released their BAO final measurements covering eight distinct redshift intervals, obtained and improved over the past 20 years [35]. Given the importance of these data for cosmology in recent years, here we perform a brief analysis for comparison with our measurements, using the $D_V(z)/r_d$, $D_M(z)/r_d$, and $D_H(z)/r_d$ measurements compiled in Table 3 in [35], regarding BAO-only data. In what follows, we call this data compilation by SDSS (BAO). We assume that the uncertainties are Gaussian approximations to the likelihoods for each tracer ignoring the correlations between measurements (as suggested in the SDSS collaboration paper).

Fig. 4 Parametric space in the $H_0 - \Omega_m$ plane inferred from $\theta_{BAO} + \text{BBN}$, SDSS (BAO) final release + BBN, and $\theta_{BAO} + \text{SDSS (BAO) final release} + \text{BBN}$ joint analyses. The H_0 parameter is measured in units of $\text{km s}^{-1} \text{Mpc}^{-1}$

Figure 4 shows the 68% CL and 95% CL regions in the $H_0 - \Omega_m$ plane from $\theta_{BAO} + \text{BBN}$, SDSS (BAO) + BBN, and $\theta_{BAO} + \text{SDSS (BAO) + BBN}$ joint analysis. Evidently, the accumulation of accuracy and improvement in the measurements over the years make the analysis of SDSS (BAO) + BBN very robust in the errors determination, in a direct comparison with $\theta_{BAO} + \text{BBN}$ only (see the Fig. 4). We find $H_0 = 68.32^{+0.98}_{-1.1} \text{ km s}^{-1} \text{Mpc}^{-1}$, $r_d = 151.9^{+3}_{-2.8} \text{ Mpc}$, $\Omega_m = 0.27^{+0.015}_{-0.016}$ at 68% CL from $\theta_{BAO} + \text{SDSS (BAO) + BBN}$ joint analyses. This estimate of H_0 , influenced by SDSS (BAO) data, is in agreement with the Planck-CMB data, and in $\sim 4\sigma$ tension with the SHOES [2] value. There is no tension on the r_d parameter when compared to Planck-CMB data.

We check the individual (in)consistency between $\text{BBN} + \theta_{BAO}$ and $\text{BBN} + \text{SDSS (BAO)}$ constraints. The H_0 values obtained separately with these data sets differ in $\sim 2\sigma$, and the Ω_m parameter is in full statistical compatibility one to each other.

4 Final remarks

We obtained accurate constraints on H_0 and r_d parameters, independently of CMB data and local distance ladder data. In this work we are motivated to look how recent transversal BAO measurements (that is, from θ_{BAO} estimates [34]), in combination with other model-independent data sets, can bound these parameters and what direction do they take in light of recent observational tensions, especially in the context of the H_0 tension. We find an accuracy of $\sim 2.6\%$ and $\sim 1.7\%$ on H_0 from $\theta_{BAO} + \text{BBN} + \text{H0LiCOW}$ and

Fig. 5 Parametric space in the $H_0 - \Omega_m$ plane inferred from $\theta_{BAO} + \text{BBN}$, CC + BBN and H0LiCOW+BBN. The H_0 parameter is measured in units of $\text{km s}^{-1} \text{Mpc}^{-1}$

$\theta_{BAO} + \text{BBN} + \text{CC}$, respectively. We observe that both values are compatible with local estimates of H_0 , and in tension with Planck data only and some joint analyses in combination with other BAO compilations of the literature. Our results show that it is possible to use a robust compilation of BAO data, i.e., the θ_{BAO} compilation, in such a way that the tension on the H_0 parameter is minimized or even not exist, when compared to local and model-independent measurements.

An interesting perspective regards the measurements of transversal BAO data. With arriving new data from ongoing astronomical surveys we expect new transversal BAO measurements, with both features: more precise estimates and performed at diverse redshifts. In fact, these data has shown potential to constrain better r_d and H_0 , important quantities in modern cosmology because they provide absolute scales to measure the Universe evolution at opposite sides.

Consistency between θ_{BAO} , CC, and H0LiCOW samples

The aim of this section is to show that the θ_{BAO} , CC, and H0LiCOW data sets are consistent with each other. These analyses are important because make clear for the readers that these data sets can be combined properly without worrying about any possible inconsistency and/or tensions between them. Thus, these data can be used in joint analyses to test phenomenological models and hypotheses in cosmology.

Figure 5 shows the parametric space in the $H_0 - \Omega_m$ plane inferred from $\theta_{BAO} + \text{BBN}$, CC + BBN, and BBN+H0LiCOW. The BBN information is taken for improve any possible degeneracy in the total matter density. We can conclude that these three data sets, i.e., θ_{BAO} , CC, and H0LiCOW samples, are fully consistent with each other at $\lesssim 1\sigma$.

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