Cosmological parameter analyses using transversal BAO data

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Abstract. Current data analyses combine diverse cosmological probes to break degeneracy between cosmological parameters using, for instance, the data from Type IA supernova data or from Baryon Acoustic Oscillations (BAO). Regarding the use of the BAO data, this can lead to biased inferences of the cosmological parameters in study because the comoving BAO sound horizon at drag epoch, $r_{\text{drag}}$, used to quantify the BAO measurements $H(z)$ and $D_A(z)$, is inferred from a combination of cosmic microwave background (CMB) data and a theoretical model, as WMAP and Planck collaborations did. One can avoid possibly biased analyses combining CMB data in conjunction with a set of 15 measurements of the transversal BAO scale, considered cosmological model-independent to explore, via Monte Carlo Markov chains, the parametric space of some cosmological models. We investigate how much Planck CMB data in combination with transversal BAO measurements can constraints the minimum $\Lambda$CDM model, and extensions including additional parameters as $r_{\text{drag}}$, neutrinos mass scale $M_\nu$, and the possibility for a dynamical dark energy model. Assuming the $\Lambda$CDM cosmology, we find $H_0 = 69.23 \pm 0.50$ km s$^{-1}$ Mpc$^{-1}$, $M_\nu < 0.11$ eV and $r_{\text{drag}} = 147.59 \pm 0.26$ Mpc from Planck + transversal BAO data. When assuming a dynamical dark energy cosmology, we find that the inclusion of the BAO data can indeed break the degeneracy of the dark energy free parameters, improving the constraints on the full parameter space significantly. We note that the model is compatible with local measurements of $H_0$ and there is no tension on $H_0$ estimates. Also, we discuss the results from a joint analysis with the latest local $H_0$ measurement. Finally, we perform a model-independent analysis for the deceleration parameter $q(z)$ from our compilation of the transversal BAO data.

Keywords: Cosmological parameters, Baryonic acoustic oscillations, Dark energy
1 Introduction

Nowadays are stimulating for cosmology, with a plethora of dark energy models competing to describe the current high-quality cosmological observations [1, 2]. The combination of data from cosmological probes like standard candles, from type Ia supernovae data [3], standard rulers, from Baryon Acoustic Oscillations (BAO) data [4–6], together with measurements of the cosmic microwave background (CMB) radiation [7, 8] have produced precise parameters constraints of the concordance cosmological model, the spatially flat ΛCDM [8–10], strongly restricting alternative scenarios (see, e.g., [11–20]).

To investigate cosmological models or parameters using observational data one usually performs a likelihood approach, which is done under basic assumptions. At the end, some hypothesis can be changed and the possible dependence of the results on such modification is studied. This is the case of the analyses of the CMB temperature fluctuations measurements, based on a power-law spectrum of adiabatic scalar perturbations, done by the Planck collaboration using a combination of temperature, polarization, and lensing CMB data. They found [8] that the best-fit values of the spatially flat six parameter (i.e., Ω\textsubscript{b} h\textsuperscript{2}, Ω\textsubscript{c} h\textsuperscript{2}, θ\textsubscript{⋆}, τ, A\textsubscript{s}, n\textsubscript{s}) ΛCDM model (here termed minimum ΛCDM) provides a good consistency with the data, with no indications for a preference on extensions of this basic set of parameters and hypotheses. Assuming this minimum ΛCDM cosmology, the Planck collaboration also found derived model-dependent parameters: H\textsubscript{0}, Ω\textsubscript{m}, and σ\textsubscript{8} [8]. Additionally, combining CMB data with BAO measurements, they found [8] that the neutrino mass is tightly constrained to M\textsubscript{ν} < 0.12 eV, and that the effective extra relativistic degrees of freedom agrees with the prediction of the Standard Model N\textsubscript{eff} = 3.046.

Clearly, one cannot expect that the whole parameter space of the model will be well-behaved when describing the set of distinct cosmological probes used in several combined analysis. This is the case with the CMB lensing amplitude and the parameters related to, in fact, it was reported that the CMB spectra prefer higher lensing amplitudes than predicted in the minimum ΛCDM at over 2 σ [8]. Another recognized tension is that one reported for the Hubble parameter H\textsubscript{0}: while local SNIa observations measure H\textsubscript{0} = 74.03 ± 1.42 [21], the likelihood analyses of the derived parameters of the Planck collaboration result in H\textsubscript{0} = 67.4 ± 0.5 km s\textsuperscript{-1}Mpc\textsuperscript{-1} [8]. And the question is how much dependent on model hypotheses are these results? [22, 23], or do they reflect just measurements with underestimated systematics? [24] (for examples of how systematics can influence data analyses see, e.g., [25–29]).
In any case, it seems very convenient to perform new analyses considering a set of model-independent BAO measurements, and this is the main goal of the current work. In fact, it is worth to remember that the BAO measurements are sometimes obtained adopting a fiducial cosmology in two levels. First, the BAO data, \( H(z) \) and \( D_A(z) \), depend on the value of the sound horizon at drag epoch, \( r_{\text{drag}} \), which is obtained with CMB data and assuming various cosmological model hypotheses like \( \Lambda \)CDM scaling rules for the matter, radiation, and dark energy components, the validity of cosmological perturbations in the frame of general relativity, etc. [7, 8, 22, 23]. Second, the radial BAO scale determining \( H(z) \) involves the computation of 3-dimensional radial distances calculated after assuming a fiducial cosmology. Instead, the transversal BAO scale can be obtained in thin redshift bins of data without assuming a fiducial model, but the final measurement is weakly dependent on cosmological parameters (see, e.g., [30–34]).

Moreover, efforts are being done in the literature to obtain the sound horizon \( r_{\text{drag}} \) almost model-independently [22, 23]. Following this objective, we shall combine data from Planck 2018 CMB data together with BAO, but using only the transversal BAO model-independent data \( D_A(z; r_{\text{drag}}) \). Complementing these analyses, we add the local Hubble parameter measurement [21] as a prior allowing a still more precise determination of \( r_{\text{drag}} \) at low redshift, in specific cases where the \( H_0 \) tension is not present.

On the other hand, the neutrinos play a crucial role in the dynamics of our Universe, by inferring direct changes in the clustering of structures and, consequently, in the determination of cosmological parameters (see an incomplete list of works that investigates neutrino features [35–45] and references therein). The standard parameters that characterize these effects are the effective number of neutrino species \( N_{\text{eff}} \) and the total neutrino mass scale \( M_\nu \). We refer to [8, 45] for most recent constraints on these parameters. In principle, both quantities \( N_{\text{eff}} \) and \( M_\nu \) are model dependent, and hence, different cosmological scenarios may bound these parameters in different ways. In our analyses, we consider that model-independent measurements of the transversal BAO can help to a better constraint of the neutrinos mass scale. It will be the first time that such data sets will be used to investigate these properties of neutrinos.

According to this plan, we combine for the first time quasi model-independent angular BAO measurements, with the following aims:

(i) To perform combined analyses that explores the parameters space of some dark energy (DE) models and, additionally, to obtain a precise estimate of \( r_{\text{drag}} \) from each model.

(ii) To derive new bounds on the neutrino mass scale \( M_\nu \) within \( \Lambda \)CDM and extended models, considering the possibility for some dynamical dark energy scenarios, robustly using transversal BAO data.

(iii) An independent model analysis to reconstruct the deceleration parameter \( q(z) \) from our compilation of transverse BAO data.

The cosmological model analyses mentioned above in the points (i) and (ii) encompass two scenarios: the current concordance model, i.e., the spatially flat \( \Lambda \)CDM, and the simplest natural extension to the \( \Lambda \)CDM model, that is, a dynamical DE model, \( w_0-w_a \)CDM considering the Chevallier-Polarski-Linder (CPL) parameterization [53, 54], where the EoS is characterized by \( w(a) = w_0 + w_a(1-a) \), where \( a \) is the scale factor in a Friedmann-
Robertson-Walker cosmology.

Our main results show that the joint analyses of CMB data and transversal BAO measurements improves the parameter constraints, also in the case where we include the neutrino mass as an extra-parameter. Moreover, we also recover the best-fit values of the minimum ΛCDM model [8], concerning the basic and derived cosmological parameters, with improved values when including BAO data.

This work is organized as follows. In the next section, we present our data set and the statistical methodology adopted. In section 3 we present the results and the related discussion of our analyses. In section 4 we perform a model-independent analysis on the $q(z)$ function from the transversal BAO data and section 5, we summarize the findings of our analyses and future perspectives.

2 Data and Methodology

In what follows, we describe the observational data sets used in this work. First, we describe the set of 15 transversal BAO measurements, $θ_{BAO}(z)$, obtained in a quasi model-independent approach. In fact, in a thin redshift bin with suitable number density of cosmic tracers –like quasars or galaxies–, one can perform the 2-point angular correlation function between pairs to find and measure the BAO angular scale $θ_{BAO}(z)$, at that redshift (see, e.g., [32] and refs. therein). A BAO angular scale measurement gives the angular diameter distance $D_A$ at the redshift $z$

$$D_A(z; r_{\text{drag}}) = \frac{r_{\text{drag}}}{(1 + z)θ_{BAO}(z)},$$  

provided that one has a robust estimate of $r_{\text{drag}}$, the sound horizon at baryon drag epoch.

This set of 15 transversal BAO measurements [32, 33, 46–48], were obtained using public data releases (DR) of the Sloan Digital Sky Survey (SDSS), namely: DR7, DR10, DR11, DR12, DR12Q (quasars) [1]. This data set is displayed in Table 1.

| $z$ | $θ_{BAO}$ [deg] | $σ_{BAO}$ [deg] | ref. |
|-----|----------------|----------------|------|
| 0.11| 19.80          | 3.26           | [48] |
| 0.235| 9.06          | 0.23           | [46] |
| 0.365| 6.33          | 0.22           | [46] |
| 0.45 | 4.77          | 0.17           | [32] |
| 0.47 | 5.02          | 0.25           | [32] |
| 0.49 | 4.99          | 0.21           | [32] |
| 0.51 | 4.81          | 0.17           | [32] |
| 0.53 | 4.29          | 0.30           | [32] |
| 0.55 | 4.25          | 0.25           | [32] |
| 0.57 | 4.59          | 0.36           | [47] |
| 0.59 | 4.39          | 0.33           | [47] |
| 0.61 | 3.85          | 0.31           | [47] |
| 0.63 | 3.90          | 0.43           | [47] |
| 0.65 | 3.55          | 0.16           | [47] |
| 2.225| 1.85          | 0.33           | [33] |

Table 1: The angular BAO model-independent measurements from luminous red galaxies, blue galaxies, and quasars catalogs, from diverse releases of the Sloan Digital Sky Survey.
To break the degeneracy, considering the full parametric space of the models under study in this work, we shall combine this BAO data set (see Table 1) together with the CMB data from the final release of the Planck collaboration (2018), including the full likelihood [8, 49, 50]. Notice that, these CMB data correspond to the temperature and polarization data, the cross-correlation of temperature and polarization power spectra, and the lensing power spectrum likelihood. Moreover, in some analyses, we shall consider the recently measured new local value of the Hubble constant by the Hubble Space Telescope (HST): $H_0 = 74.03 \pm 1.42$ km s$^{-1}$ Mpc$^{-1}$ as reported in [21]. This value of the Hubble constant is in tension, at 4.4σ, with the Planck 2018 cosmological parameters calculation within the minimum $\Lambda$CDM model [8]. We refer to this datum as R19.

Let us consider two scenarios for our analyses. The first scenario, termed $\Lambda$CDM + $M_\nu$, considers the set of parameters

$$\mathcal{P} \equiv \{\omega_b, \omega_{cdm}, 100\theta_s, \tau_{reio}, n_s, \log[10^{10} A_s], M_\nu\}, \quad (2.2)$$

where the first six parameters corresponds to the minimum $\Lambda$CDM model: the baryon and the cold dark matter energy densities $\omega_b$ and $\omega_{cdm}$, the ratio between the sound horizon and the angular diameter distance at decoupling $100\theta_s$, the reionization optical depth $\tau_{reio}$, and the spectral index and the amplitude of the scalar primordial power spectrum $n_s$ and $A_s$, respectively.

With respect to the neutrino properties, we impose a prior of $M_\nu > 0$, ignoring a possible lower limit from the neutrino oscillations experiments and assuming fixed three neutrinos species, that is, $N_{eff} = 3.046$. For the purposes of obtaining bounds on neutrino mass from the cosmological data, the prior $M_\nu > 0$ is adequate.

The second scenario considers a dynamical DE model, where the EoS is given in terms of the CPL parametrization, let us call this model by $w_0$-$w_a$CDM model. In this case, the parametric space is written as

$$\mathcal{P} \equiv \{\omega_b, \omega_{cdm}, 100\theta_s, \tau_{reio}, n_s, \log[10^{10} A_s], w_0, w_a, M_\nu\}, \quad (2.3)$$

where $w_0$ and $w_a$, are free parameters that characterize the dynamics of the EoS, where for $w_0 = -1$ and $w_a = 0$, we recovered the $\Lambda$CDM model.

We use the publicly available CLASS [55] and MontePython [56] codes to analyze the free parameters of the models defined above. We used Metropolis Hastings algorithm with uniform priors on the full baseline parameters to obtain correlated Markov Chain Monte Carlo samples. We have ensured the convergence of the chains for all parameters according to the Gelman-Rubin criterium.

In the statistical analyses, we consider the flat priors on all parameters, the common baseline parameters in all scenarios is: $100\omega_b \in [0.8, 2.4]$, $\omega_{cdm} \in [0.01, 0.99]$, $100\theta_s \in [0.5, 2]$, $\tau_{reio} \in [0.01, 0.8]$, $\log_{10}(10^{10} A_s) \in [2, 4]$, $n_s \in [0.9, 1.1]$, $w_0 \in [-3, 0]$, $w_a \in [-3, 3]$, and $M_\nu \in [0, 1]$. In what follows we discuss our results.

### 3 Combined analyses of CMB plus transversal BAO data

Throughout this section we will present our main results using observational data from diverse cosmological tracers, assuming the scenarios defined in the previous section. For the $\Lambda$CDM + $M_\nu$ model, we summarize the main observational results in Table 2. For comparison, we also show analyses without and with neutrinos.
Planck + BAO

0

3

67

0

0

74

Showing compatibility between Planck and transversal BAO data, including the difference on these parameters between the analyses Planck + transversal BAO versus to a higher (lower) fit value as compared to the analysis with the Planck data only. However, the units of km/s/Mpc, $H_0$, $w$, $\Omega_m$, $\sigma_8$, $r_{\text{drag}}$.

Table 2: Constraints at 68% and 95% CL on free and some derived parameters under $\Lambda$CDM model baseline from the considered data combinations. The parameter $H_0$ is measured in the units of km/s/Mpc, $r_{\text{drag}}$ in Mpc, whereas $M_\nu$ is in the units of eV.

| Parameter | Planck | Planck + BAO |
|-----------|--------|--------------|
| $\Omega_m$ | 0.1192$^{+0.0113}_{-0.0082}$ | 0.1192$^{+0.0113}_{-0.0082}$ |
| $H_0$ | 66.59$^{+0.60}_{-0.10}$ | 66.59$^{+0.60}_{-0.10}$ |
| $\sigma_8$ | 0.823$^{+0.010}_{-0.012}$ | 0.823$^{+0.010}_{-0.012}$ |
| $r_{\text{drag}}$ | 147.09$^{+0.01}_{-0.01}$ | 147.09$^{+0.01}_{-0.01}$ |

Table 3: Constraints at 68% and 95% CL on free and some derived parameters under $w_0$-$w_a$ CD M model baseline from the considered data combinations. The parameter $H_0$ is measured in the units of km/s/Mpc, $r_{\text{drag}}$ in Mpc, whereas $M_\nu$ is in the units of eV.

Assuming the $\Lambda$CDM scenario, we notice that adding the transversal BAO data (see Table 1) for a combined analysis, the constraints on the parameters that are most sensitive to geometrical tests, like $\Omega_m$ and $H_0$, are significantly improved. In fact, in the Planck + transversal BAO analysis, the constraint of the parameter $H_0$ ($\Omega_m$) is significantly deviated to a higher (lower) fit value as compared to the analysis with the Planck data only. However, the difference on these parameters between the analyses Planck + transversal BAO versus Planck data only, as well as the full parameter space, are compatible with each other even at 68% CL. Showing compatibility between Planck and transversal BAO data, including the
### Constraints in the Planck + BAO + R19 parameter space

**Table 1:** Constraints in the plan \( \Omega_{\text{m}} \) - \( M_{\nu} \), under perspectives of the scenario \( \Lambda \text{CDM} + M_{\nu} \).

**Figure 1:** Results from the \( \Lambda \text{CDM} \) cosmology. Left panel: Constraints at 68% and 95% CL in the parametric space \( r_{\text{drag}} - H_0 \) from Planck data only and Planck + transversal BAO, with and without the addition of neutrinos mass scale \( M_{\nu} \) as a free parameter. Right panel: Constraints in the plan \( \Omega_{m0} - M_{\nu} \), under perspectives of the scenario \( \Lambda \text{CDM} + M_{\nu} \).

The value obtained by the Planck team from CMB + BAO data is \( H_0 = 67.77 \pm 0.42 \) km/s/Mpc, whereas \( M_{\nu} \) is in the units of eV.

1See section 5.1 in [8] for details of the BAO data points, obtained assuming a fiducial cosmology, used in the analyses done by the Planck collaboration.
**Figure 2**: Left panel: The 68% CL. and 95% CL. regions in the plan $r_{\text{drag}} - H_0$ inferring from $w_0 - w_a$CDM model using Planck data only and Planck + transversal BAO. Right panel: The same as left panel, but a joint analysis from Planck + transversal BAO + R19. The vertical light red band corresponds to measure $H_0 = 74.03 \pm 1.42$ km s$^{-1}$ Mpc$^{-1}$.

**Figure 3**: Left panel: Parametric space at 68% CL and 95% CL in the plan $w_0 - w_a$ from the considered data combinations. Right panel: Confidence regions at 68% CL and 95% CL in the plan $M_\nu - w_0$ from the $w_0 - w_a$CDM model in terms of the considered data combinations.

is well reported in the literature that there is a strong tension between the $H_0$ calculation done by the Planck collaboration and local measurements as reported by Riess et al. [21], i.e., $H_0 = 74.03 \pm 1.42$ km s$^{-1}$ Mpc$^{-1}$. One can notice that the combined analyses done here, using Planck + transversal BAO data, minimally alleviate this tension, but a tension at more than 3$\sigma$ still remains. The difference on the $H_0$ parameter between the Planck team constraints and our results is, approximately, 1.4$\sigma$.

In the left panel of Figure 1, we show the confidence level contours in the parametric space $r_{\text{drag}} - H_0$ from all our analyses using the minimum $\Lambda$CDM parameters. Some words are in due here regarding $r_{\text{drag}}$, the comoving sound horizon at the baryon drag epoch.
This quantity is not directly measured by CMB data, its calculation depends on model hypotheses of early time physics, for this it is obtained in a model-dependent way in CMB analyses \[8, 22, 23\]. Both parameters, \( r_{\text{drag}} \) and \( H_0 \), provide an absolute scale for distance measurements at opposite ends of the observable universe, \( r_{\text{drag}} \) (early time) and \( H_0 \) (late time). When measured with the same data, these parameters must agree with the values predicted by the standard cosmological model. Otherwise, significant deviations of these parameters with respect to the expected values would provide indications for some new physics beyond the standard model, or unaccounted systematic errors in the measurements.

Planck team reported the value \( r_{\text{drag}} = 147.21 \pm 0.23 \) from CMB + BAO at 68% CL in \( \Lambda \)CDM cosmology \[8\]. These estimates are not only compatible, but very similar to ours, in all analyses (see Table 2). On the other hand a model-independent reconstruction from the early-time physics shows that \( r_{\text{drag}} = 136.7 \pm 4.1 \) \[57\]. As argued in \[57\], this strong tension in the \( r_{\text{drag}} \) measurement is entirely due to the tension in the \( H_0 \) parameter, via the strong correlation between the quantities \( H_0 \) and \( r_{\text{drag}} \).

Considering a physics beyond the standard model, in ref. \[58\] it is assumed a dark coupling between dark matter and photons, an approach that can reconcile the tension in both parameters, \( H_0 \) and \( r_{\text{drag}} \). Another proposal for some new physics in light the \( H_0 \) and \( r_{\text{drag}} \) tension at early and/or late time modification in the standard cosmological model was also proposed in the refs. \[59–66\].

In the right panel of Figure 1, we show the confidence level contours in the parametric plane \( \Omega_m - \Omega_\nu \), where we find \( \Omega_\nu < 0.11 \) eV at 95% CL from Planck + transversal BAO data. That boundary on the neutrino mass scale is practically the same as that one reported by the Planck team using Planck CMB + BAO, i.e., \( \Omega_\nu < 0.12 \) eV. Some minimal displacement can be noted on the \( \Omega_m \) best fit value, but again, the constraints are fully compatible with each other at 68% CL. Thus, we conclude that the combination of the transversal BAO and CMB data can bound \( \Omega_\nu \) with the same accuracy than other joint analyses reported in the literature.

On the other hand, in view of the capacity of the transversal BAO data to breaks the degeneracy on some cosmological parameters, let us study how these data could bound some dynamical effect of the dark energy density. In Table 3, we summarize the results of our statistical analyses from the perspective of the \( w_0-w_a \)CDM model, that is, a cosmological model with a dynamical dark energy. As already known, assuming a \( w_0-w_a \)CDM model, the constraints on \( H_0 \) become degenerate in such way to obtain high \( H_0 \) values enough to be compatible with local measurements made by the HST team (see \[45\] and references there). We combine Planck CMB data with transversal BAO data to break the degeneracy on the full baseline parameters of the model, finding \( H_0 = 74.1^{+2.4}_{-3.3} \) km s\(^{-1}\) Mpc\(^{-1}\) (without including neutrinos) and \( H_0 = 75.6^{+2.4}_{-3.5} \) km s\(^{-1}\) Mpc\(^{-1}\) (including neutrinos), both at 68% CL. Thus, we can clearly notice that by adding transversal BAO, the analysis significantly improve the bounds on the \( H_0 \) parameter (see the \( H_0 \) value from Planck data only in the Table 3 for this scenario). Additionally, these constraints are fully compatible with the measurement \( H_0 = 74.03 \pm 1.42 \) km s\(^{-1}\) Mpc\(^{-1}\) from R19. Thus, the current tension on \( H_0 \) present in \( \Lambda \)CDM model, does not persist within this scenario, and the combination Planck + transversal BAO is compatible, with the R19 datum. We conclude that dynamic models, like \( w_0-w_a \)CDM, can solve the tension in the value of \( H_0 \). In view of this, let us also consider the joint analysis Planck + transversal BAO + R19 data. These results are summarized in the Table 4.

In the Figure 2 we show the parametric space in the plane \( r_{\text{drag}} - H_0 \). On the left panel,
we quantify the improvements due to the inclusion of the transversal BAO data. On the right panel, we have the joint analyses Planck + transversal BAO + R19. With respect to the \( r_{\text{drag}} \) parameter, we do not notice any significant deviations as compared with the results predicted for the minimum \( \Lambda \)CDM model, in the Planck collaboration analyses [8].

In the left panel of Figure 3 we show the constraints in the plane \( w_0 - w_a \) from Planck data in joint analyses with transversal BAO and R19 data. Notably, one can notice how much the transversal BAO data set significantly improves the constraints on the EoS parameters of the DE, in comparison with Planck data only. We found no evidence for deviations from the minimum \( \Lambda \)CDM cosmology, even when including the R19 datum in the analyses. In the right panel of Figure 3 we show the relationship between \( w_0 - M_\nu \) and the effect on the confidence contour levels due to diverse combined data analyses. We observe that the bound on the neutrino mass scale is slightly decreased, while the constraints on the \( w_0 \) parameter are more robust, significantly improving the restrictions when considering the joint analysis Planck + BAO and Planck + BAO + R19. That is, we found \( M_\nu < 0.38, 0.33, 0.31 \) eV at 95% CL, from Planck, Planck + BAO, and Planck + BAO + R19 data sets, respectively. The final effect is that the presence of a dynamical dark energy component slightly extends the bound on \( M_\nu \), as compared to the \( \Lambda \)CDM model. Effects of the neutrino mass scale on some parametric dynamical dark energy models are also discussed in [67–69], but these studies consider other data sets. Our results represents a new update on \( M_\nu \) through the use of these recent transversal BAO data compilation.

The \( w_0 - w_a \)CDM scenario predict less dark matter today –in contrast, more dark energy– via the relation \( \Omega_m + \Omega_{DE} = 1 \), where \( \Omega_m = \Omega_b + \Omega_{DM} \), in direct comparison with the \( \Lambda \)CDM best fit values. Notice that \( \Omega_b \) is fully compatible in all these scenarios. So, the change on \( \Omega_m \) estimates is due to dark matter density only, once the radiation (photons + neutrinos) contribution is negligible at \( z = 0 \). Because this scenario predicts more dark energy at late times, the universe expands faster than predicted in the \( \Lambda \)CDM cosmology, 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), where the amplitude of the ISW effect will depend on the duration of the dark energy-dominated phase, which is basically managed by the ratio \( \Omega_{DM}/\Omega_{DE} \). The \( H_0 \) value is inferred from the CMB data 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 \( \Omega_{DM}/\Omega_{DE} \) and \( H_0 \) mainly. The \( w_0 - w_a \)CDM scenario is changing primarily the \( D_{A}^* \) history, because a faster expansion at late times increases the angular diameter distance to the surface of last scattering, thus generating a greater value of \( H(z = 0) = H_0 \).

4 Model independent reconstruction of \( q(z) \)

In this section, we find cosmological model independent constraints on the deceleration parameter, \( q(z) \), directly from analyses of the transversal BAO data. In order to do so, we use the so-called Gaussian Processes (GP) [70, 71]. In what follows, we briefly describe the methodology.

The GP method consists of considering Gaussian errors on data, so that the function that should describe the data correctly could be seen as a random normal variable. The method is explained in refs. [70–72]. As the data points are expected to be related through
the same underlying function $f(x)$, two points $x$ and $x'$ are correlated through a covariance function (or kernel) $k(x, x')$. By choosing such a covariance function, the distribution of functions is described by

\[
\begin{align*}
\mu(x) &= \langle f(x) \rangle, \\
k(x, x') &= \langle (f(x) - \mu(x))(f(x') - \mu(x')) \rangle, \\
\text{Var}(x) &= k(x, x).
\end{align*}
\] (4.1)

There are many choice options of the covariance functions, but without loss of generality, we shall focus on the Gaussian (or Squared Exponential) kernel, which is given by

\[
k(x, x') = \sigma_f^2 \exp \left[ -\frac{(x - x')^2}{2l^2} \right], \] (4.2)

where $\sigma_f$ and $l$ are the so called hyperparameters. The GP method consists on optimizing for $\sigma_f$ and $l$ and then using (4.1) for reconstruct the function $f(x)$.

We use the freely available software GaPP\(^2\) in order to reconstruct $q(z)$ from the $\theta_{\text{BAO}}$ data. First, we have tried to reconstruct $\theta_{\text{BAO}}(z)$. However, we have found that the reconstruction of $\theta_{\text{BAO}}(z)$ does not yield reliable results. As explained in [70], given the same amount of data, functions that change very rapidly are more difficult to reconstruct than smooth functions. It happens that $\theta_{\text{BAO}}(z)$ is not a smooth function of the redshift $z$. In fact, for any cosmological model, $D_A(z = 0) = 0$. As $\theta_{\text{BAO}}(z) \propto \frac{1}{D_A}$, then $\theta_{\text{BAO}}(z) \to \infty$ for $z \to 0$.

Instead, we reconstruct $D_A(z)$, which is expected to be a smooth function of the redshift ($D_A \propto z$ at low redshift for any cosmological model). In order to obtain the $D_A(z)$ data, we have used Eq. (2.1) to obtain the uncertainties through error propagation as

\[
\sigma_{D_A} = D_A \frac{\sigma_{\theta_{\text{BAO}}}}{\theta_{\text{BAO}}}. \] (4.3)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Reconstruction of $D_A(z)/r_{\text{drag}}$. The blue solid line corresponds to the median of $D_A/r_{\text{drag}}$. Also shown are the 68.3%, 95.4% and 99.7% CL regions. \textbf{Left}: Full sample. \textbf{Right}: Sample with $z < 0.7$.}
\end{figure}

The $D_A(z)$ reconstruction can be seen on Figure 4. As observed in this figure (left panel), the reconstruction performs poorly in the range $0.7 \lesssim z \lesssim 2$, due to lack of data on

\(^2\)\url{http://www.acgc.uct.ac.za/~seikel/GAPP/index.html}
Figure 5: Reconstruction of $q(z)$. Also shown are the 68% and 95% CL regions. **Left:** Analyses of the full BAO data sample. **Right:** Analyses considering the sub-sample with $z < 0.7$.

this interval. Aiming to focus on the region with more available data, we perform a second reconstruction with BAO data only up to $z < 0.7$. This is shown in Figure 4 (right panel).

As can be seen in Figure 4 (right panel), $D_A/r_{\text{drag}}$ is better constrained on $0.4 < z < 0.7$, where there is more data. For $z < 0.4$, there are only 3 data points, with a larger uncertainty for the lowest redshift datum. We believe this is the reason why the reconstruction poorly represents the expected behavior at low redshift, yielding a distance compatible with zero at $z = 0$ only at the 99.7% CL.

Also observed in Figure 4, two predictions from ΛCDM, both using $\Omega_m = 0.292$ and $r_{\text{drag}} = 147.59$ Mpc, from the best fit of Planck+BAO combination. However, we have found that $D_A$ is much sensitive to the choice of $H_0$. Thus, we show a curve with $H_0 = 69.23$ km s$^{-1}$ Mpc$^{-1}$ from Planck + BAO (dashed curve) and one with $H_0 = 74.03$ km s$^{-1}$ Mpc$^{-1}$ from R19 data (dotted curve). As can be seen the curve with higher value of the Hubble constant yields a better agreement with the data and with the GP reconstruction.

Assuming spatial flatness, it was shown in [72] that $q(z)$ can be obtained from luminosity distance $D_L(z)$. Here, we use the Etherington duality relation $D_L(z) = (1 + z)^2 D_A(z)$ to show that

$$q(z) = -\frac{(1 + z)^2 D''_A(z) + 3(1 + z)D'_A(z) + D_A(z)}{D_A(z) + (1 + z)D'_A(z)}.$$  \hfill (4.4)

From this result, the $q(z)$ function is independent of the distance dimension, so it is independent of $r_{\text{drag}}$. We show the result of this reconstruction on Fig. 5. The blue solid line corresponds to the median $q(z)$ obtained from the GP. The light blue regions correspond to the 68% and 95% CL around the median. These regions were found by sampling the multivariate normal distribution of $D_A$, $D'_A$, and $D''_A$ found from the reconstruction above. We also show the theoretical prediction for ΛCDM (dashed curve) assuming $\Omega_m = 0.292$ from Planck+BAO constraint. As can be seen, the ΛCDM model presents some tension with the reconstructed function done in light of the transversal BAO data only at low redshift, $z < 0.3$. This is probably due to the lack of data on this $z$ range. On the other hand, in the interval $0.3 < z < 0.7$, with more data, there is a nice agreement with ΛCDM cosmology with model independent reconstruction.
5 Final Remarks

We have presented a new compilation with 15 quasi model-independent angular BAO measurements summarized in Table 1 obtained from analyses of luminous red galaxies, blue galaxies, and quasars catalogs using various public data releases from the SDSS collaboration. These transversal BAO data are weakly dependent on a cosmological model, as explained in detail in refs. [30–32].

For the first time it is performed a combined analyses, using these data, to explore the parameter space of some DE models and, additionally obtaining a precise estimate of \( r_{\text{drag}} \) from each model. Furthermore, we derive new bounds on the neutrino mass scale \( M_\nu \) within \( \Lambda \)CDM and extended models, considering the possibility for some dynamical DE scenarios. In addition, we perform an independent model analyses to reconstruct the deceleration parameter \( q(z) \) from the compilation of these BAO data.

An interesting outcome of the current analyses is that the addition of BAO data helped to break possible degeneracy in the parameters space, showing the compatibility between Planck and these transversal BAO data set.

Last, but not least, we mention that the combination of the transversal BAO and CMB data can bound \( M_\nu \) with the same accuracy than other joint analyses reported in the literature. Finally, we also obtained that dynamical models, like \( w_0 - w_a \)CDM, can solve the tension in the value of \( H_0 \).

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