# Consistency tests between SDSS and DESI BAO measurements

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## Introduction and Motivation

We focus on a comparison between the state-of-the-art BAO measurements from Dark Energy Spectroscopic Instrument (DESI) and the previous releases of Sloan Digital Sky Survey (SDSS) in a model-independent way that would indicate potential systematics that might lead to discrepant conclusions about the validity of the standard cosmological model (SCM), as well as the evidence of new physics. We perform this comparison by means of non-parametric reconstructions of observable quantities, such as the cosmic expansion rate through the Hubble parameter, $H(z)$, and the deceleration parameter, $q(z)$, that can be obtained from each individual dataset and their combination.

## Analysis

### Theoretical framework

The cosmic expansion rate is given by the Hubble parameter, which reads

$$\left[\frac{H(z)}{H_0}\right]^2 = \Omega_{\rm m}(1+z)^3 + \Omega_{\rm DE}\exp\left[3\int_0^z \frac{1+w(z')}{1+z'}dz'\right], \tag{1}$$

By assuming that dark energy corresponds to the Cosmological Constant $\Lambda$, we have $w(z) = -1$, thus Eq. (1) reduces to

$$\left[\frac{H(z)}{H_0}\right]^2 = \Omega_{\rm m}(1+z)^3 + (1-\Omega_{\rm m})\,. \tag{2}$$

We can define the deceleration parameter as

$$q(z) = -\frac{\ddot{a}}{aH} = (1+z)\frac{H'(z)}{H(z)} - 1\,, \tag{3}$$

in addition to the null diagnostic $\mathcal{O}_{\rm m}(z)$, which is based on a consistency relation for the SCM:

$$\mathcal{O}_{\rm m}(z) \equiv \frac{E(z)^2-1}{(1+z)^3-1} = \Omega_{\rm m} \quad \text{in flat } \Lambda\text{CDM}\,, \tag{4}$$

where $E(z) \equiv H(z)/H_0$, so that

$$\mathcal{O}_{\rm m}(z) \neq \Omega_{\rm m} \quad \text{implies that SCM is ruled out.} \tag{5}$$

### Reconstruction method

We adopt a non-parametric approach using the Gaussian Process (GP) method. By definition, a GP consists of a distribution over functions, rather than over variables as in the case of a Gaussian distribution. We use the well-known GaPP (Gaussian Processes in Python) package throughout this work [3, 2][a], in order to obtain $H(z)$ and $H'(z)$ from the DESI and SDSS BAO data.

Error-propagation on $q(z)$ and $\mathcal{O}_{\rm m}(z)$ gives the uncertainties:

$$\left[\frac{\sigma_{q(z)}}{1+q(z)}\right]^2 = \left[\frac{\sigma_{H(z)}}{H(z)}\right]^2 + \left[\frac{\sigma_{H'(z)}}{H'(z)}\right]^2 - \left[\frac{2\sigma_{H(z)H'(z)}}{H(z)H'(z)}\right], \tag{6}$$

$$\sigma_{\mathcal{O}_{\rm m}(z)} = \left[\frac{2E(z)}{(1+z)^3-1}\right]\sigma_{E(z)}\,, \tag{7}$$

where $\sigma^2_{E(z)} = (\sigma^2_{H(z)}/H_0^2) + (H^2(z)/H_0^4)\sigma^2_{H_0}$.

### Observational data

We utilise the latest $D_{\rm H}(z)/r_{\rm d}$ BAO measurements provided by the SDSS and DESI surveys.

| $z$ | $z_{\rm eff}$ | $D_{\rm H}(z)/r_{\rm d}$ |
|---|---|---|
| $0.2 < z < 0.5$ | **0.38** | $25.00 \pm 0.76$ |
| $0.4 < z < 0.6$ | **0.50** | $22.33 \pm 0.58$ |
| $0.6 < z < 1.0$ | **0.70** | $19.33 \pm 0.53$ |
| $0.8 < z < 2.2$ | **1.48** | $13.26 \pm 0.55$ |
| $z > 1.77$ | **2.33** | $9.08 \pm 0.34$ |

| $z$ | $z_{\rm eff}$ | $D_{\rm H}(z)/r_{\rm d}$ |
|---|---|---|
| $0.4 < z < 0.6$ | **0.51** | $20.98 \pm 0.61$ |
| $0.6 < z < 0.8$ | **0.71** | $20.08 \pm 0.60$ |
| $0.8 < z < 1.1$ | **0.93** | $17.88 \pm 0.35$ |
| $1.1 < z < 1.6$ | **1.32** | $13.82 \pm 0.42$ |
| $1.77 < z < 4.16$ | **2.33** | $8.52 \pm 0.17$ |

Table 1. Baryon acoustic oscillation (BAO) measurements for SDSS (left) and for DESI DR1 (right), according to [1].

## Results

### Reconstructed $H(z)$

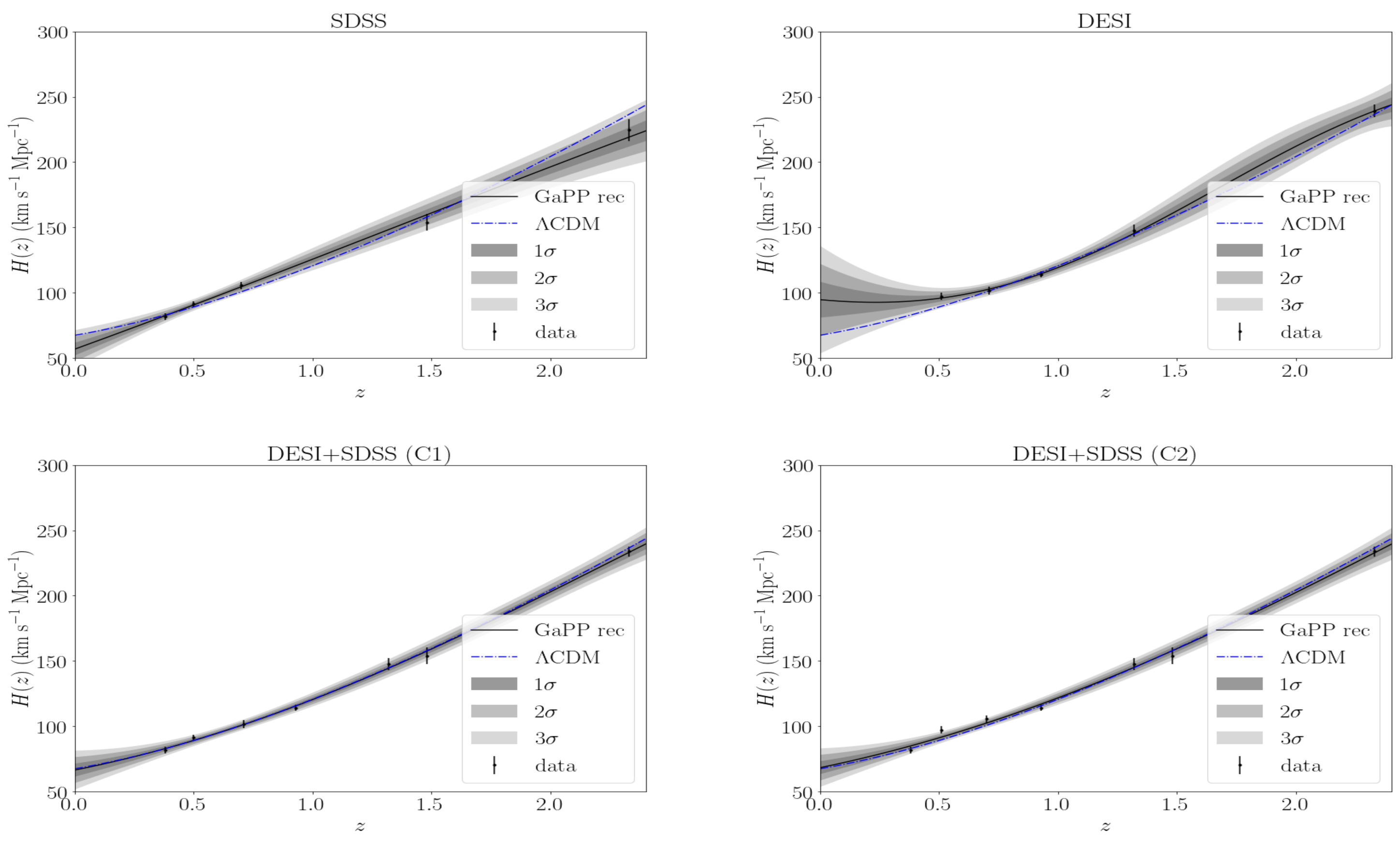


Figure 1. SDSS (top left), DESI (top right), DESI and SDSS combination 1 (bottom left), and combination 2 (bottom right). The blue dot-dashed line denotes the SCM prediction, where we assume a flat $\Lambda$CDM model given by $\Omega_{\rm m} = 0.315$ and $H_0 = 67.4$ km s$^{-1}$ Mpc$^{-1}$, as reported by Planck 2018 results.

[a]`https://github.com/astrobengaly/GaPP`

### Reconstructed $q(z)$

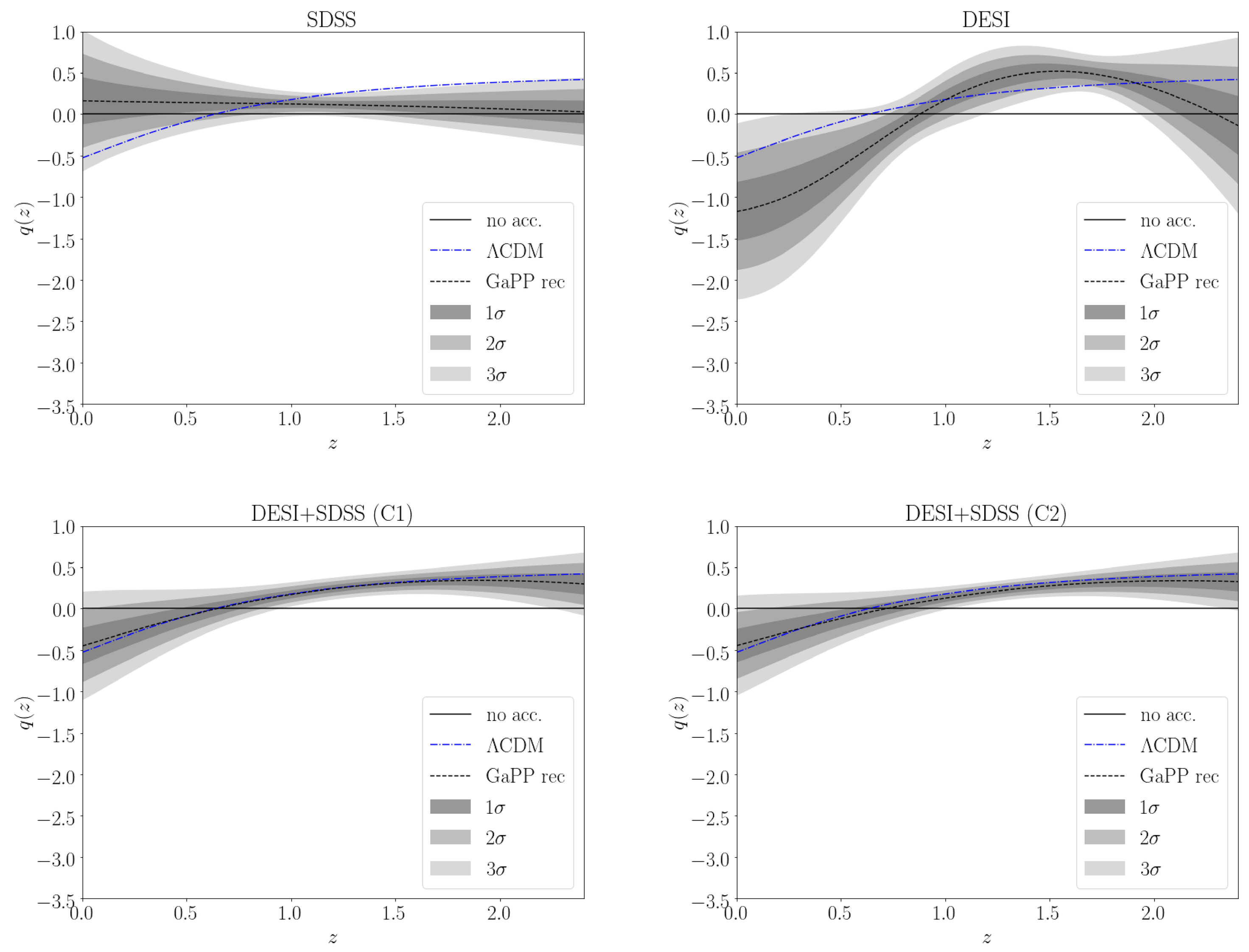


Figure 2. Same as Fig. 1, but rather for the deceleration parameter $q(z)$

### Reconstructed $\mathcal{O}_{\rm m}(z)$

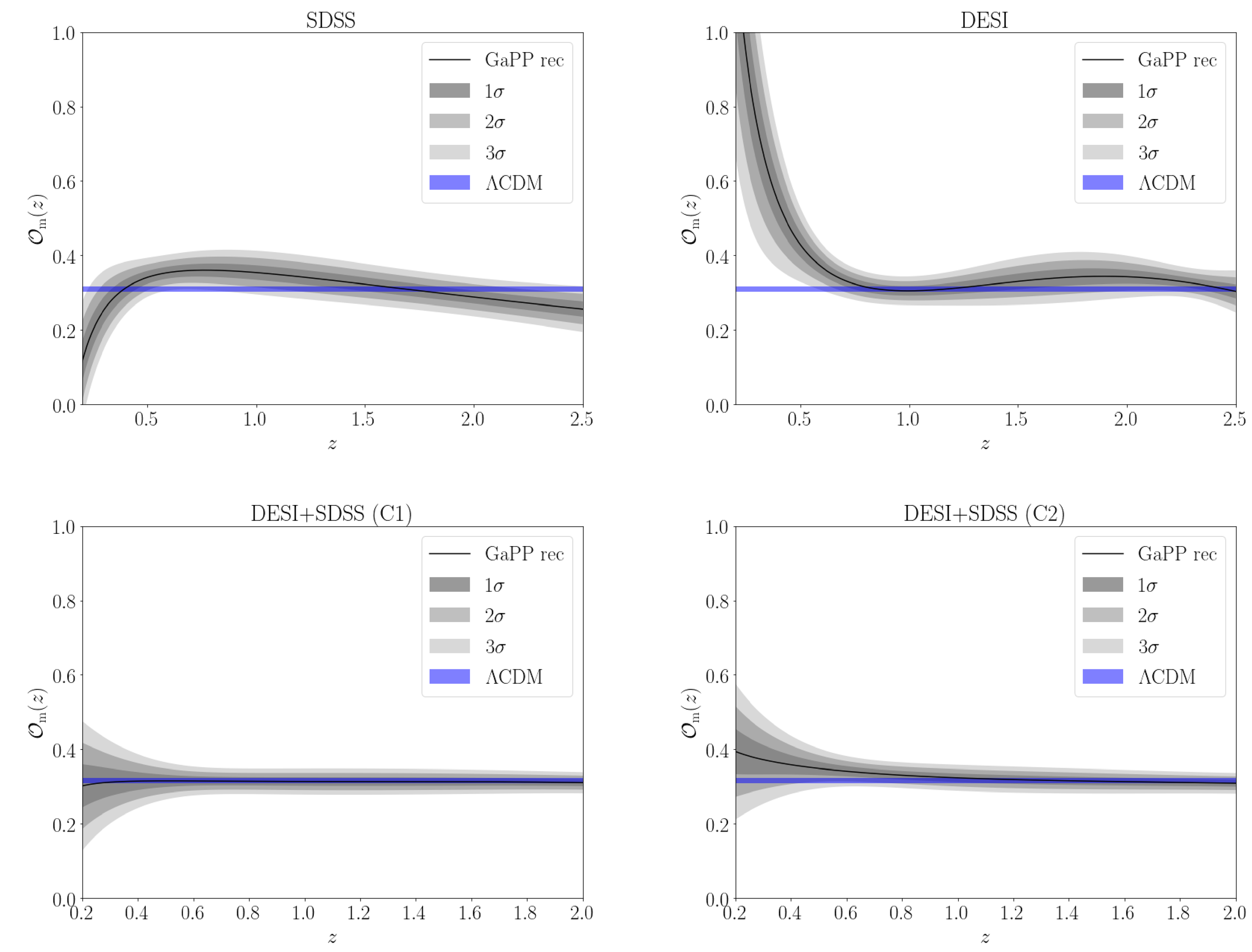


Figure 3. Same as Fig. 2, but rather for the null diagnostic $\mathcal{O}_{\rm m}(z)$. The thick blue line represents the latest Planck CMB (TT,TE,EE+lowE+lensing) constraint on $\Omega_{\rm m}$ at $1\sigma$ confidence level, that is, $\Omega_{\rm m} = 0.315 \pm 0.007$. We also assume the $H_0$ prior as the Planck 2018 best-fit in this case, i.e., $H_0 = 67.4 \pm 0.5$ km s$^{-1}$ Mpc$^{-1}$.

## Summary

- For the non-parametric reconstructions of the Hubble parameter $H(z)$, its derivative $H'(z)$, the deceleration parameter $q(z)$ and the null diagnostic $\mathcal{O}_{\rm m}(z)$, the DESI and SDSS data alone show considerable deviations from $\Lambda$CDM predictions, whereas their combinations are in remarkable agreement with the same.
- For the $q(z)$ reconstruction, the SDSS data seem to suggest that there has been no accelerated expansion of the universe. However, as expected from the DESI results, we see hints of slower accelerated expansion at present times. A combination of both datasets is in good agreement with $\Lambda$CDM.
- The $\mathcal{O}_{\rm m}(z)$ diagnostic seems to suggest that DESI alone prefers a phantom-like dark energy model, whereas SDSS alone prefers a quintessence-like dark energy model.
- We also carry out our analysis with a different GP kernel, Matern72, instead of the squared exponential one, as well as impose a different sound horizon scale assuming a low-$z$ prior. Barring some minor changes, the overall behaviour of the reconstructions for all the above cases remains the same.
- Our analysis calls for further investigation of existing results in order to address this inconsistency between SDSS and DESI. We can expect to have a better insight once the low redshift data of DESI become available and can be compared with SDSS data at similar redshifts.

## References

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