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Date: 2025-06-20T21:28:37+00:00

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Full Text

Preamble

Possible evidences for physics beyond ΛCDM from DESI DR2

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Abstract

We analyze DESI DR2 data with a model-independent method and find that: (a) the expansion of the universe may speed up with a confidence level more than 2.3σ at redshift $z_{51} \in (0.51, 0.955)$; (b) the expansion of the universe may speed down with a confidence level greater than 1.7σ at redshift $z_{75} \in (0.955, 1.484)$; (c) $w_x \leq w_t < -1$ with confidence level exceeding 1.6σ at redshift $z_{53} \in (0.922, 0.955)$.

PACS numbers:

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INTRODUCTION

Since the discovery of the phenomenon of accelerated expansion of the universe, ΛCDM (with an equation of state (EoS) $w_x = p_x/\rho_x = -1$) has attracted widespread attention for its simplest and most theoretically grounded approach. However, it also faces the crisis of the cosmological constant problem [?] and the age problem [?, ?]. In addition, the Hubble tension has posed new challenges for ΛCDM [?].

Recently, the Dark Energy Spectroscopic Instrument (DESI) collaboration presented a cosmological analysis based on the latest baryon acoustic oscillations (BAO) measurements from its Data Release 2 (DR2) [?]. Their results point to discrepancies between datasets becoming more relevant within the ΛCDM model, preferring dynamical dark energy (DDE) as a possible solution \cite{5–7}. The DESI DR2 results are consistent with the ΛCDM model, but they exhibit a 2.3σ tension [?] with cosmic microwave background (CMB) measurements (Planck data including external CMB lensing data from [?]). Using the CPL parameterization, DESI DR2 data combined with CMB temperature and polarization anisotropies, as well as CMB lensing, shows DDE is preferred at 3.1σ, increasing up to 4.2σ when including SNe data [?] (this preference is also supported by the Dark Energy Survey BAO and SNe combined analysis [?]). It is important to note that Refs. [?, ?] report preference for a DDE without the DESI dataset. Other recent research also suggests DDE, see, for example \cite{11–19}.

In [?], however, wCDM was favored by DESI 2024 data.

Using the Lagrange mean value theorem, a model-independent method was proposed to analyze $H(z)$ parameter data, and the results suggest possible evidence for physics beyond ΛCDM [?, ?]. Here we generalize this method to analyze DESI DR2 data and examine whether we can obtain similar evidence beyond ΛCDM. We find that the universe may experience accelerated expansion during $0.51 < z < 0.955$ and the EoS of dark energy may be less than -1 during $0.922 < z < 0.955$.

The paper is structured as follows. In Sec. II, we present the DESI DR2 data and the method needed to analyze the data. In Sec. III, we provide the results obtained from the analysis. In Sec. IV, we give conclusions and discussions.

II. DESI DR2 DATA AND METHODOLOGY

In this section, we outline the DESI DR2 data released recently and generalize the method proposed in [?, ?], which is needed for data analysis.

A. DESI DR2 Data

Baryon acoustic oscillations from galaxy surveys constrain the expansion history of the universe during $0.1 < z < 4.2$, probing the matter-dominated era and the recent era of cosmic acceleration. The most precise BAO measurements to date come from DESI, which incorporates observations of millions of galaxies and quasars. These measurements provide an unprecedented dataset that enables the construction of detailed 3D maps of the cosmic web, facilitates precise measurements of the universe's expansion history [?, ?], and provides robust constraints on the EoS parameter of dark energy [?, ?].

The BAO measurements from DESI are expressed as the transverse comoving distance D_M/r_d, the angle-averaged distance D_V/r_d, and the Hubble horizon D_H/r_d, all normalized to the comoving sound horizon at the drag epoch r_d. Here we are interested in the F data from DESI DR2 [?], shown in Table I, where $F \equiv D_M/D_H$.

For a spatially flat universe, the Hubble distance D_H and the transverse comoving distance D_M are defined, respectively, as:

$$D_H = \frac{c}{H(z)}$$

$$D_M = (1+z)D_A = \int_0^z \frac{c\,dz'}{H(z')}$$

with $H(z)$ the Hubble function.

TABLE I: F data obtained from DESI's BAO measurement [?].

index	z	F
0	0.510	0.622 ± 0.017
1	0.706	0.892 ± 0.021
2	0.922	1.232 ± 0.021
3	0.934	1.223 ± 0.019
4	0.955	1.220 ± 0.033
5	1.321	1.948 ± 0.045
6	1.484	2.386 ± 0.136
7	2.330	4.518 ± 0.097

B. Methodology

From the Planck 2018 results: $\Omega_{K0} = 0.001 \pm 0.002$ [?], we consider a universe described by the spatially flat Friedmann-Robertson-Walker-Lemaître (FRWL) metric:

$$ds^2 = -dt^2 + a^2(t)\left[dr^2 + r^2(d\theta^2 + \sin^2\theta\,d\phi^2)\right]$$

with $a(t)$ the scale factor. The Friedmann equations are given by:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

$$\dot{H} = -4\pi G(\rho + p)$$

where the dot indicates derivative with respect to cosmic time t and we use units where $c = 1$.

The total energy density ρ and the corresponding pressure p include contributions from radiation, nonrelativistic matter, and other components. To determine whether the expansion of the universe is speeding up, a physical quantity called the deceleration parameter is required, defined as:

$$q \equiv -\frac{\ddot{a}a}{\dot{a}^2}$$

In data fitting, we often need another form of expression for it:

$$q = -1 + (1+z)\frac{d\ln H}{dz} = -1 + \frac{1+z}{E(z)}\frac{dE(z)}{dz}$$

where $E(z) = H(z)/H_0$. In terms of the deceleration parameter, the total EoS $w_t = p_t/\rho_t$ can be written as:

$$w_t = \frac{2q-1}{3}$$

For a spatially flat universe, the parameter F reduces to:

$$F = \frac{D_M}{D_H} = E(z)\int_0^z \frac{dz'}{E(z')}$$

which implies:

$$\frac{dF}{dz} = \frac{E(z) + (1+z)\frac{dE}{dz}}{E(z)}F - \frac{(1+z)}{E(z)}$$

Therefore, the deceleration parameter can be rephrased as:

$$q = -1 + \frac{1+z}{F}\frac{dF}{dz}$$

Now we generalize the model-independent method introduced in [**?**, **?**] to establish a basic framework for analyzing DESI DR2 data. Assuming that the parameter F is continuously differentiable, we have from the Lagrange mean value theorem in calculus:

$$F'(z_{ij}) \equiv \left.\frac{dF}{dz}\right|_{z=z_{ij}} = \frac{F(z_i) - F(z_j)}{z_i - z_j}$$

where $z_j < z_{ij} < z_i$. If we approximate the value of $F(z_i)$ at redshift z_i with the datum $F_o(z_i)$ at $1\sigma_{F(z_i)}$ confidence level, then we can approximate $F'(z_{ij})$ as:

$$F'(z_{ij}) \approx \frac{F_o(z_i) - F_o(z_j)}{z_i - z_j}$$

at $1\sigma_{F'}$ confidence level, where:

$$\sigma_{F'} = \frac{\sqrt{\sigma^2_{F(z_i)} + \sigma^2_{F(z_j)}}}{z_i - z_j}$$

Now considering the approximation of the deceleration parameter and using the above expression, we have:

$$q(z_{ij}) \approx -1 + \frac{1 + z_{ij}}{F(z_{ij})} \left(\frac{F(z_i) - F(z_j)}{z_i - z_j} \right)$$

at $1\sigma_q$ confidence level, where σ_q is given by:

$$\sigma_q = \frac{1 + z_{ij}}{F(z_{ij})} \sigma_{F'}$$

In the equation above, we have adopted the mid-value approximation method [**?**]: $z_{ij} \approx (z_i + z_j)/2$ and $F(z_{ij}) \approx [F(z_i) + F(z_j)]/2 \approx [F_o(z_i) + F_o(z_j)]/2$.

III. APPLICATIONS

When using the equations above to analyze the observational F parameter data from Table I, the error σ_q would be amplified if $z_i - z_j \ll 1$. Therefore, we impose the following limitations during the analysis process to ensure credible results: $0.1 \leq z_i - z_j \leq 0.5$. The obtained q and w_t data are presented in Table II with 1σ confidence level.

From these data, we can draw the following conclusions:

(a) During the period $0.51 < z < 0.955$, the universe may experience an accelerated phase. For example, the expansion may accelerate with confidence level exceeding 2σ at redshift $z_{41} \in (0.51, 0.934)$; with significance greater than 2.3σ at redshift $z_{51} \in (0.51, 0.955)$; and with more than 1.6σ at redshifts $z_{52} \in (0.706, 0.955)$ and $z_{53} \in (0.922, 0.955)$.

(b) During the period $0.934 < z < 1.484$, the universe may experience a decelerated phase. For example, the expansion may decelerate with confidence level exceeding 1σ at redshifts $z_{64} \in (0.934, 1.321)$ and $z_{74} \in (0.934, 1.484)$; with more than 1.6σ at redshift $z_{65} \in (0.955, 1.321)$; and with greater than 1.7σ at redshift $z_{75} \in (0.955, 1.484)$.

(c) We find $w_x \leq w_t < -1$ with confidence level more than 1σ at redshift $z_{43} \in (0.922, 0.934)$, and exceeding 1.6σ at redshift $z_{53} \in (0.922, 0.955)$.

According to the Planck 2018 results [**?**], the phase transition from deceleration to acceleration of the universe occurred at redshift $z \approx 0.632$ for a spatially-flat ΛCDM model, which is consistent with result (b) here. However, it is not consistent with result (c) and the accelerated expansion at redshifts z_{52} and z_{53} in result (a). Results (a) and (c) may suggest possible evidence for physics beyond ΛCDM.

IV. CONCLUSIONS AND DISCUSSIONS

Generalizing the model-independent method proposed in [**?**, **?**], we have analyzed DESI DR2 data with the corresponding confidence levels. From the obtained data, we come to the following conclusions: **(a)** the universe may have experienced an accelerated phase during the era $0.51 < z < 0.955$; **(b)** the universe may have experienced a decelerated phase during the era $0.934 < z < 1.321$; **(c)** the EoS of dark energy may be less than -1 during the era $0.922 < z < 0.955$.

Result (c) suggests that there may exist an accelerated phase before the current accelerating period.

The obtained $q(z)$ and w_t data may be used to test cosmological models. The results here depend on the DESI DR2 data. In future research, more and more accurately measured BAO data will be needed to validate our findings. The method provided here could be generalized to analyze other observational data.

TABLE II: q and w_t obtained from DESI's BAO measurement.

index	z	q	w_t
$z_{41} \in (0.51, 0.934)$	-0.22 ± 0.11	-0.48 ± 0.07	
$z_{51} \in (0.51, 0.955)$	-0.35 ± 0.15	-0.57 ± 0.10	
$z_{42} \in (0.706, 0.934)$	-0.22 ± 0.22	-0.48 ± 0.14	
$z_{52} \in (0.706, 0.955)$	-0.45 ± 0.27	-0.63 ± 0.18	
$z_{43} \in (0.922, 0.934)$	-3.75 ± 3.70	-2.83 ± 2.47	
$z_{53} \in (0.922, 0.955)$	-3.16 ± 1.89	-2.44 ± 1.26	
$z_{64} \in (0.934, 1.321)$	0.17 ± 0.16	-0.22 ± 0.10	
$z_{74} \in (0.934, 1.484)$	0.36 ± 0.26	-0.09 ± 0.17	
$z_{65} \in (0.955, 1.321)$	0.33 ± 0.20	-0.11 ± 0.13	
$z_{75} \in (0.955, 1.484)$	0.48 ± 0.28	-0.01 ± 0.19	

Acknowledgments

This study is supported in part by the National Natural Science Foundation of China (Grant No. 12333008) and the Hebei Provincial Natural Science Foundation of China (Grant No. A2021201034).

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Note: Figure translations are in progress. See original paper for figures.