Does DESI 2024 Confirm ΛCDM?

E. Ó Colgáin,[1] M. G. Dainotti,[2,3,4] S. Capozziello,[5,6,7] S. Pourojaghi,[8] M. M. Sheikh-Jabbari,[9] and D. Stojkovic[10]

[1]*Atlantic Technological University, Ash Lane, Sligo, Ireland*
[2]*Division of Science, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, 181-8588 Tokyo, Japan*
[3]*The Graduate University for Advanced Studies (SOKENDAI), Shonankokusaimura, Hayama, Miura District, Kanagawa 240-0115, Japan*
[4]*Space Science Institute, Boulder, CO, USA*
[5]*Dipartimento di Fisica "E. Pancini" , Universitá degli Studi di Napoli "Federico II" Complesso Univ. Monte S. Angelo, Via Cinthia 9 80126, Napoli, Italy*
[6]*Scuola Superiore Meridionale, Largo S. Marcellino 10, 80138, Napoli, Italy*
[7]*Istituto Nazionale di Fisica Nucleare (INFN), Sez. di Napoli, Complesso Univ. Monte S. Angelo, Via Cinthia 9, 80126, Napoli, Italy*
[8]*Department of Physics, Bu-Ali Sina University, Hamedan 65178, 016016, Iran*
[9]*School of Physics, Institute for Research in Fundamental Sciences (IPM), P.O.Box 19395-5531, Tehran, Iran*
[10]*HEPCOS, Department of Physics, SUNY at Buffalo, Buffalo, NY 14260-1500, USA*

We demonstrate that a $\sim 2\sigma$ discrepancy with the Planck-ΛCDM cosmology in DESI Luminous Red Galaxy (LRG) data at $z_{\rm eff} = 0.51$ translates into an unexpectedly large Ω_m value, $\Omega_m = 0.668^{+0.180}_{-0.169}$. We independently confirm that this anomaly drives the preference for $w_0 > -1$ in DESI data confronted to the $w_0 w_a$CDM model. We show that redshift bins of DESI constraints allow Ω_m to wiggle at the $\sim 2\sigma$ level with increasing effective redshift in the ΛCDM model. Given that LRG data at $z_{\rm eff} = 0.51$ is at odds with Type Ia supernovae in overlapping redshifts, we expect that this anomaly will decrease in statistical significance with future DESI data releases leaving an increasing Ω_m trend with effective redshift at higher redshifts. We estimate the significance of the latter in DESI data at $\sim 1.8\sigma$ and comment on how it dovetails with independent observations. It is imperative to understand what makes DESI LRG data at $z_{\rm eff} = 0.51$ an outlier when it comes to Ω_m determinations.

I. INTRODUCTION

In the absence of observational systematics, cosmological tensions [1–3] and pre-calculus demand that we see changes in the ΛCDM model parameters when confronted to data in different redshift bins [4, 5]. Conversely, if one recovers the same ΛCDM parameters within the errors when one confronts the model to data at different redshifts, then systematics are at play. In practice, testing all redshift ranges is not feasible, but we should endeavour to test as many redshift ranges as possible. The community is in the process of testing the consistency of the (flat) ΛCDM model. See [6] for an overview of results.

Recently, the Dark Energy Spectroscopic Instrument (DESI) collaboration has released its first round of cosmological constraints based on baryon acoustic oscillations (BAO) [7, 8], providing hints of evolution in the dark energy (DE) sector [9]. Consider the $w_0 w_a$CDM model with redshift dependent DE equation of state, $w(z) = w_0 + (1-a) w_a = w_0 + z/(1+z) w_a$, where a is the scale factor, z is the redshift, and $(w_0, w_a) = (-1, 0)$ [10, 11] recovers ΛCDM. In this context, DESI reports a preference for $w_0 > -1$, which is driven by the Luminous Red Galaxy (LRG) sample with effective redshift $z_{\rm eff} = 0.51$. Combining DESI with Planck CMB data [12] and Type Ia supernovae (SNe), including Pantheon+ [13], Union3 [14] and DES [15], the preference for $w_0 w_a$CDM model over ΛCDM increases to 2.5σ, 3.5σ and 3.9σ, respectively [9].

While nothing precludes folding different data sets together and confronting them to the the $w_0 w_a$CDM model, care is required with physics. In cosmology, physics demands that observables are singing from the same hymn sheet. In short, late-time accelerated expansion is only believable if CMB, BAO, SNe, and many other data sets agree on its existence. Turning this argument around, DESI claims of dynamical dark energy are only believable if BAO and SNe show consistent deviations from the ΛCDM model in similar redshift ranges. If they contradict each other, then statistical fluctuations, systematics, or evolutionary effects with redshifts not properly treated, are at play somewhere.

In this letter we take a closer look at the implications of DESI data for the ΛCDM model on the grounds that if $w_0 w_a$CDM model is preferred over ΛCDM model, then this must be evident in changes or evolution of the ΛCDM paramaters with binned or effective redshift. Through this exercise, we find that DESI LRG data prefers larger $\Omega_m \sim 0.65$ values of matter density at $z_{\rm eff} = 0.51$. Independent of DESI analysis [9], we confirm that this redshift range is responsible for the preference for $w_0 > -1$ in the the $w_0 w_a$CDM model. Moreover, binning DESI data reveals $\sim 2\sigma$ variations in Ω_m between bins. Given that no other cosmological probe has a preference for $\Omega_m \sim 0.65$ at lower redshifts, in particular SNe do not, we argue that a statistical fluctuation and/or systematics are at play either in DESI or SNe data. Finally, we speculate that an increasing Ω_m trend with effective redshift at higher redshift, one discernible in DESI data, is physical by invoking similar observations in independent probes.

II. FLAT ΛCDM

In this section we look for signatures of varying ΛCDM cosmological parameters in DESI data [9]. The motivation is cosmological tensions [1–3], where it is necessary to diagnose potential shortcomings of the model by performing consistency checks of the model [6].

A. Markov Chain Monte Carlo

In Table I we employ MCMC [16] to determine the 68% confidence intervals for ΛCDM parameters from anisotropic BAO constraints in Table 1 of [9]. The observables include LRG, emission line galaxies (ELG) and the Lyman-α forest (Lyα QSO). The justification for focusing largely on anisotropic BAO is that, as is evident from Fig. 2 [9], isotropic BAO from the bright galaxies (BGS) and QSO cannot determine Ω_m, and isotropic BAO only constrains posteriors to curves in the (H_0, Ω_m)-plane. One can combine the posteriors, but the price one pays is putting observables at $z_{\rm eff} = 0.3$ and $z_{\rm eff} = 1.49$ in the same bin. Throughout we incorporate the correlation between D_M/r_d and D_H/r_d constraints, where r_d denotes the radius of the sound horizon at the baryon drag epoch and

$$D_M(z) := \frac{c}{H_0}\int_0^z \frac{dz'}{E(z')}, \qquad D_H(z) := \frac{c}{H(z)} \qquad (1)$$

where H_0 is the Hubble parameter, $H(z) = H_0 E(z)$ is the Hubble diagram and c is speed of light. Without external data or assumptions, it is impossible to separate H_0 from r_d, so we quote confidence intervals for the combination $H_0 r_d$ alongside Ω_m.

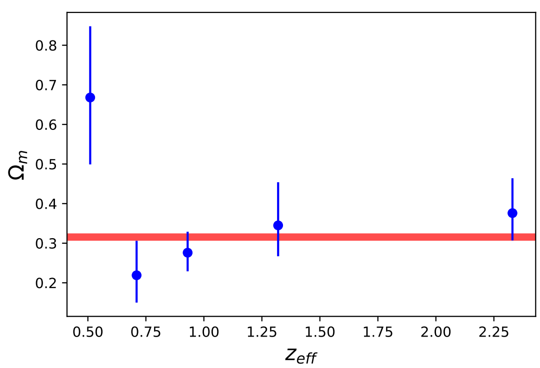

FIG. 1. 68% confidence intervals for Ω_m versus effective redshift $z_{\rm eff}$. Neglecting the DESI LRG constraint at $z_{\rm eff} = 0.51$, the data shows excellent agreement with the corresponding Planck-ΛCDM confidence interval in red.

From Table I, there are essentially two features to highlight. First, the LRG data at $z_{\rm eff} = 0.51$ leads to a surprisingly large value of Ω_m that is discrepant with the Planck value $\Omega_m = 0.315 \pm 0.007$ [12] at the $\sim 2.1\sigma$ level. It is difficult to interpret this result, as it is also at odds with the Pantheon+ SNe constraint $\Omega_m = 0.334 \pm 0.018$ [13] at the $\sim 2\sigma$ level.[1] Note, SNe samples typically have low effective redshifts of $z_{\rm eff} \sim 0.3$. Thus, in contrast to Planck versus DESI LRG, where one has observables at different redshifts, Pantheon+ versus DESI LRG, is a disagreement in an overlapping redshift range. While it may be tempting to interpret the DESI result as a fluctuation in data, DESI has confirmed that the constraint in that redshift range is consistent with SDSS [9]. Unsurprisingly, as can be seen from Fig. 5 of [17], SDSS BAO [18] does lead to larger Ω_m values in similar redshift ranges. This makes a statistical fluctuation explanation less likely.

tracer	$z_{\rm eff}$	$H_0 r_d$ [100 km/s]	Ω_m
LRG	0.51	$88.34^{+5.66}_{-4.75}$	$0.668^{+0.180}_{-0.169}$
LRG	0.71	$109.36^{+6.08}_{-6.08}$	$0.219^{+0.087}_{-0.069}$
LRG+ELG	0.93	$102.17^{+4.10}_{-4.02}$	$0.276^{+0.053}_{-0.047}$
ELG	1.32	$97.78^{+7.65}_{-8.02}$	$0.345^{+0.109}_{-0.078}$
Lyα QSO	2.33	$92.79^{+7.60}_{-7.46}$	$0.375^{+0.088}_{-0.069}$

TABLE I. 68% confidence intervals from DESI anisotropic BAO constraints at effective redshift $z_{\rm eff}$.

The second feature of interest is an increasing Ω_m/decreasing $H_0 r_d$ with effective redshift beyond the anomalous LRG constraint. The trend is evident in Fig. 1 and Table I. This trend is expected if observations of similar trends in strong lensing time delay, both lensed QSOs [19–21] and SNe [22, 23],[2] type Ia SNe [17, 25–29] (see also [30–32] for related discussions), observational Hubble data (OHD) [26, 33], combinations of OHD and SNe [26, 34], GRBs [35], and standardsiable QSOs [17, 26, 36–41] hold up.

As an aside, there is a growing body of work in literature either questioning [42–46] or improving the Risaliti-Lusso standardisable QSO prescription [39, 47, 48]. Nevertheless, despite the corrections imposed on the QSO data, residual evolution of the Ω_m parameter is still reported [47–49]. Moreover, DES SNe have a higher effective redshift [15], so the larger Ω_m value is consistent with these observations. Going beyond established probes such as SNe, QSOs [36, 37] and GRBs [50–56] calibrated by SNe, may also return larger values of Ω_m at higher redshifts. [3] Returning to the main point, if not for the LRG Ω_m constraint at $z_{\rm eff} = 0.51$, one could add the four highest redshift DESI constraints from Fig. 1 to the corroborating support for the increasing Ω_m/decreasing H_0 trend.

[1] The relatively large LRG Ω_m errors mean that doubling the Ω_m error from CMB to SNe, while shifting the central value upwards, has little bearing on the statistical significance of the disagreement.

[2] The claim is particularly clear from Fig. 5 of [23] (see also [24]), where it is evident that the error bars of H_0 determined from SN Refsdal and SN H0pe do not overlap, placing the disagreement at $\sim 1.5\sigma$. Note that SN H0pe has a lens redshift of $z = 0.35$, whereas the lens redshift of SN Refsdal is $z = 0.54$, thereby making Fig. 5 of [23] consistent with the descending trend of H_0 with lens redshift reported originally in Wong et al. [19] (see appendix).

[3] This could be mundanely due to large scatter in the data and not due to any variation in the ΛCDM parameters. One can separate these two possibilities by comparing to SNe in overlapping redshift regimes [17].

z	$H_0 r_d$ [100 km/s]	Ω_m
$0.1 < z < 0.6$	$96.13^{+3.81}_{-3.94}$	$0.459^{+0.120}_{-0.098}$
$0.6 < z < 1.1$	$106.82^{+3.09}_{-3.08}$	$0.231^{+0.036}_{-0.033}$
$1.1 < z < 4.16$	$98.59^{+4.29}_{-4.27}$	$0.324^{+0.044}_{-0.038}$

TABLE II. 68% confidence intervals from DESI anisotropic and isotropic BAO binned by redshift. From bin 1 to bin 2 Ω_m shifts downwards by $\sim 2.2\sigma$ and from bin 2 to bin 3 Ω_m shifts upwards by $\sim 1.8\sigma$.

To assess the statistical significance of the increasing Ω_m/decreasing $H_0 r_d$ trend at higher redshifts, as well as the impact of the DESI constraint at $z_{\rm eff} = 0.51$, we introduce the remaining two isotropic BAO constraints from Table 1 of the DESI paper [9]. The corresponding 68% confidence intervals are shown in Table II in redshift bins, where it is evident that Ω_m starts off high at lower redshifts, decreases at intermediate redshifts, before increasing again at larger redshifts. The statistical significance of the shifts in the Ω_m parameter are $\sim 2.2\sigma$ and $\sim 1.8\sigma$, respectively. As DESI is designed to produce a much larger number of constraints at a wide range of redshifts [57], it will be important to revisit these two features with future releases. Note, at $\sim 2\sigma$ one can of course ignore these results, but it is well established that matter density is approximately 30% in the ΛCDM Universe. This now comes with the caveat that there is a corner of the Universe probed by DESI where matter density is 65%; the inconsistency is striking.

Before moving on, we revisit Fig. 3 of [9] to comment on the discrepancies with Planck, $\Omega_m = 0.315 \pm 0.007$ [12], Pantheon+, $\Omega_m = 0.334 \pm 0.018$ [13], Union3, $\Omega_m = 0.356^{+0.028}_{-0.026}$ [14], and DES, $\Omega_m = 0.352 \pm 0.017$ [15], data sets. Once again, we use all the data, both anisotropic and isotropic BAO constraints. For all constraints in Table 1 of [9] we find $\Omega_m = 0.290^{+0.015}_{-0.014}$. This agrees well with our best fit or maximum likelihood estimator (MLE) of $\Omega_m = 0.289$. Note, the central value we find is slightly lower than Table 3 of the DESI paper [9]. This sets the disagreement with Planck, Pantheon+, Union3 and DES at $\sim 1.5\sigma$, $\sim 1.9\sigma$, $\sim 2.2\sigma$ and $\sim 2.7\sigma$, respectively. While all disagreements are below a 3σ threshold, they are serious enough that further study is warranted. It is fitting to recall the claim originally made in [17] that the fitting parameter Ω_m is not a constant and evolves, or more precisely increases, with effective redshift.

Finally, we remove the LRG contraint at $z_{\rm eff} = 0.51$. Doing so, we expect the Ω_m value to decrease, and it does to $\Omega_m = 0.287^{+0.016}_{-0.015}$ with an MLE of $\Omega_m = 0.286$. Overall, the shift downwards is not pronounced, and the error inflates, but this increases the tension with DES to $\sim 2.8\sigma$. Evidently, the working assumption that Ω_m is a constant in the ΛCDM Universe is under pressure at close to 3σ. This needs to be put in context. Given H_0 tension, a problem in background cosmology,[4] and $S_8 = \sigma_8 \sqrt{\Omega_m/0.3}$ tension, a seemingly perturbative problem, it is important to recognise that both these problems can be related provided we find a discrepancy in Ω_m [6]. The reason being that H_0 is correlated with Ω_m at the background level in the late Universe and S_8 clearly depends on Ω_m. If Ω_m is not a constant in the ΛCDM model, then H_0 and S_8 tensions are symptoms of the same underlying problem.

B. A second look

In this section we adopt complementary methodology following [17]. This provides an independent check on the results from anisotropic BAO in Table I. The basic idea is to employ the fact that the ratio

$$\frac{D_M/r_d}{D_H/r_d} = E(z) \int_0^z \frac{1}{E(z')} {\rm d}z', \tag{2}$$

only depends on Ω_m in the ΛCDM model for which $E(z) = \sqrt{1 - \Omega_m + \Omega_m (1+z)^3}$.

Eq. (2) allows one to numerically solve for Ω_m.[5] To incorporate the errors, one employs the 68% confidence intervals and the correlation r to construct a 2×2 covariance matrix for each effective redshift. From the covariance matrix, one randomly generates a large number (approx. 10,000) of $(D_M/r_d, D_H/r_d)$ pairs in a multivariate normal distribution. For each pair $(D_M/r_d, D_H/r_d)$, one solves the right hand side of (2) for Ω_m. This builds up a distribution of Ω_m values from which one extracts the mean and the 68% confidence intervals in Table III. More precisely, we determine the 68% confidence interval by identifying the 15.9 and 84.1 percentiles. Throughout we assume that the Ω_m distribution is Gaussian, but as is evident from the errors in Table III, and Fig. 2, this is not a bad approximation [6]. The main take-away is that Table I and Table III show excellent agreement in central values and errors. From the outset, this may not have been expected as (2) removes all dependence on $H_0 r_d$, so one is only constraining Ω_m. Smaller errors may have been expected, but this was not the case.

tracer	$z_{\rm eff}$	Ω_m
LRG	0.51	$0.652^{+0.212}_{-0.169}$
LRG	0.71	$0.210^{+0.082}_{-0.068}$
LRG+ELG	0.93	$0.268^{+0.052}_{-0.045}$
ELG	1.32	$0.330^{+0.101}_{-0.076}$
Lyman-α QSO	2.33	$0.362^{+0.084}_{-0.066}$

TABLE III. 68% Ω_m confidence intervals from DESI anisotropic BAO constraints at effective redshift $z_{\rm eff}$ using Eq. (2).

[4] $H_0 = H(z=0)$ is determined by extrapolating the Hubble parameter, itself a solution to the Einstein equations, from low redshifts to $z = 0$.

[5] We check solutions to a precision of 10^{-10} by reinserting the solution in (2).

[6] In principle, for non-Gaussian posteriors one may fit a different distribution and this has a bearing on the errors [58]. Here we expect any difference to be small.

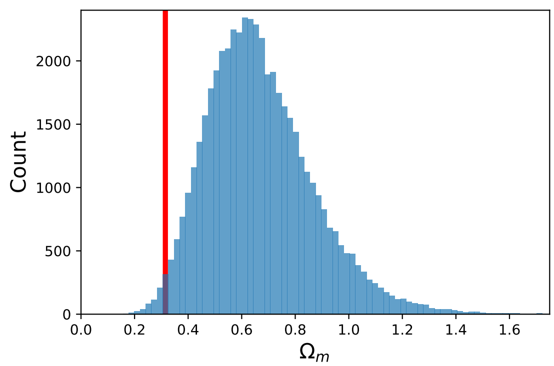

FIG. 2. Distribution of 50,000 Ω_m values at $z_{\rm eff} = 0.51$ alongside Planck constraints $\Omega_m = 0.315 \pm 0.007$ in red. The probability of finding an Ω_m value within the Planck 1σ confidence interval or lower is $p = 0.015$ corresponding to 2.2σ.

Using Eq. (2) we revisit the anomaly in LRG data evident in Fig. 2. We increase the number of configurations to 50,000, where we find a probability of $p = 0.0147$ of getting a value lower than $\Omega_m = 0.322$, the upper bound on the Planck 68% confidence intervals. This places the disagreement in Ω_m at no less than 2.2σ.

III. $w_0 w_a$CDM MODEL

From Fig. 1 and Fig. 2 it is clear that LRG data at $z_{\rm eff} = 0.51$ disagrees with the Planck-ΛCDM model at the $\gtrsim 2\sigma$ level. Moreover, as explained earlier, this constraint on Ω_m also disagrees with Pantheon+ [13] at the $\sim 2\sigma$ level, despite Type Ia SNe being most sensitive to comparable redshift ranges. As emphasised, this disagreement between DESI and Pantheon+ SNe, and more generally any SNe data set, since all closely agree on $\Omega_m \sim 0.3$ at lower redshifts, warrants further exploration. That point aside, while DESI constraints on the wCDM model from Table 3 of [9] are consistent with a cosmological constant interpretation ($w = -1$) within 1σ, fits of the $w_0 w_a$CDM model leads to a different conclusion that $w = w_0 > -1$ is preferred at in excess of 2σ. This overestimates the significance as the w_a parameter is poorly constrained and this necessitates combining DESI with CMB and SNe.

We demonstrate here that this deviation from ΛCDM is driven by LRG data at $z_{\rm eff} = 0.51$. This is acknowledged in the DESI paper [9], so our goal here is to provide independent confirmation. We employ MCMC with uniform DESI priors, $w_0 \in [-3, 1], w_a \in [-3, 2]$ and $w_0 + w_a < 0$. The key point is that if data prefers the $w_0 w_a$CDM model over ΛCDM, then changes in the ΛCDM parameters with effective (or binned) redshift must be evident in the ΛCDM model. In Fig. 3 we confirm that removing the most striking deviation from Planck-ΛCDM behaviour in Fig. 1 returns w_0 to $w_0 \sim -1$. We remark that one can clearly see the effect of DESI priors, especially the w_a and $w_0 + w_a$ priors, on confidence intervals in the (w_0, w_a)-plane; w_a is poorly constrained without external data.

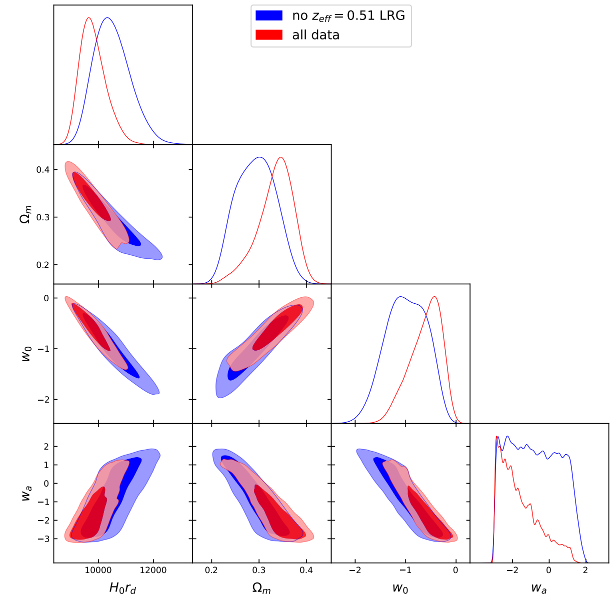

FIG. 3. $w_0 w_a$CDM model with and without LRG data at $z_{\rm eff} = 0.51$. Any hint of dynamical DE, in particular $w_0 > -1$, in DESI data is driven by LRG data. We acknowledge use of *GetDist* [59].

Concretely, we find $w_0 = -0.560^{+0.266}_{-0.384}$ with the anomalous LRG data and $w_0 = -0.984^{+0.427}_{-0.422}$ without. Evidently, w_a is pushed to large negative values that are beyond the priors to accommodate $w_0 > -1$. This comes as no surprise, since neglecting the LRG data, DESI shows excellent agreement with Planck-ΛCDM. One concludes that any hint of dynamical DE in DESI data is driven by the LRG data. Moreover, one also concludes that the strong significances for dynamical DE quoted in the DESI paper when DESI is combined with CMB and SNe, rest at least in part on an inconsistency between BAO and SNe at lower redshifts, $z_{\rm eff} \sim 0.5$. Without understanding the origin of this disagreement, claims of dynamical DE are premature.

IV. DISCUSSION

With its own data DESI has reported hints [9] of a preference for an evolving DE equation of state in the $w_0 w_a$CDM model. As explained in the original paper, and confirmed here in Fig. 1 and Fig. 3, the preference for $w_0 > -1$ can be traced to the LRG data with $z_{\rm eff} = 0.51$. While the tension with Planck-ΛCDM is only at the $\sim 2\sigma$ level, translated into familiar ΛCDM parameters, DESI LRG data at $z_{\rm eff} = 0.51$ favours a $\Omega_m \sim 0.65$ best fit. This places DESI LRG constraints at odds not only with Planck, but also with multiple type Ia SNe samples [13–15], where it should be stressed that the effective redshift is not dissimilar; SNe samples are typically biased to lower redshifts. Given that SDSS and DESI constraints agree [9], it should come as no surprise that SDSS also prefers larger

Ω_m in the same range [17] (see Fig. 5), but admittedly not quite as large. Thus, it may be hard to argue that $\Omega_m \sim 0.65$ at $z_{\rm eff} = 0.51$ is a statistical fluctuation in the data.

Arguably the great success of the ΛCDM model is that CMB, BAO and SNe agree that the Universe is 70% dark energy, $\Omega_m \sim 0.3$. In cosmology, physics must be supported by multiple observables, otherwise one is looking at statistical fluctuations or observational systematics, here either in LRG constraints at $z_{\rm eff} = 0.51$ or in 3 SNe samples.[7] This is the main take-away message from this letter. Of course, one can draw comparisons in the behaviour of the $w_0 w_a$CDM model, but care is required to make sure one is seeing consistent deviations from ΛCDM in independent observables in the same redshift ranges, otherwise claims of new physics are not compelling, no matter what interest is generated [60–65].

As is evident from Table II, even in DESI data confronted to the ΛCDM model, shifts of $\sim 2\sigma$ are evident in Ω_m as the data is binned. Concretely, Ω_m decreases with effective redshift before increasing again. $H_0 r_d$ is anti-correlated with Ω_m, so it increases and decreases again. Historically, type Ia SNe samples have shown similar trends [66, 67], but this is not overly surprising given that large SNe samples are typically compiled from different surveys. As the number of surveys grows, observational systematics become a greater concern. Nevertheless, in recent years, the Pantheon+ sample has been demonstrated to largely return consistent Ω_m values [13], provided one neglects high redshift SNe [29]. In the case of DESI, one is looking at a single survey, but multiple tracers.

The big picture here is that persistent ΛCDM tensions, most notably discrepancies in H_0 and $S_8 = \sigma_8 \sqrt{\Omega_m/0.3}$ [1–3], assuming they are physical in origin, demand that the ΛCDM model breaks down through cosmological (fitting) parameters that change with effective redshift [4, 5].[8] In support, observations of decreasing H_0/increasing Ω_m values with increasing effective redshift have been reported in a host of observables [17, 19–23, 25–29, 33–37, 41]. If substantiated, these findings point to a breakdown of the ΛCDM model at the *background level* in the late Universe. Coincidentally, observations also exist to localise S_8 tension, an apparent problem *at the perturbative level*, to the late Universe, $z \lesssim 2$ [71–74]. See [6] for a review of the science case supporting redshift evolution of ΛCDM parameters.

The situation is finely balanced. DESI has started data releases and constraints are expected to improve in coming years [57]. If the anomaly in LRG data at $z_{\rm eff} = 0.51$ persists, then BAO and CMB+SNe, and potentially even CMB and SNe [15], are at odds on Ω_m. On the flip side, if improved data quality decreases the tension with Planck, Pantheon+ etc, it is plausible that the decreasing Ω_m/increasing $H_0 r_d$ trend at lower redshifts disappears leaving an increasing Ω_m/decreasing H_0 that is seen elsewhere.

ACKNOWLEDGMENTS

DS is partially supported by the US National Science Foundation, under Grants No. PHY-2014021 and PHY-2310363. MMShJ would like to acknowledge SarAmadan grant INSF No. 4026712 and ICTP HECAP section where this project was carried out. M.G. acknowledge the support of Division of Science at NAOJ. SP would like to acknowledge the support of the Iran National Science Foundation (INSF) for the research funding provided under project No. 4024802. This article/publication is based upon work from COST Action CA21136 – "Addressing observational tensions in cosmology with systematics and fundamental physics (CosmoVerse)", supported by COST (European Cooperation in Science and Technology).

[7] These samples are not fully independent, so it is not implausible that systematics persist in SNe. Pantheon+ and Union3 share ∼ 1360 SNe, while Pantheon+ and DES share 196 SNe.

[8] One could argue that S_8 is a scale problem, e. g. [68, 69], but this cannot resolve the statistically more significant H_0 tension problem. Moreover, shifts in S_8 due to changes in scale appear too small to resolve S_8 tension [70].

[1] E. Di Valentino, O. Mena, S. Pan, L. Visinelli, W. Yang, A. Melchiorri, D. F. Mota, A. G. Riess and J. Silk, "In the realm of the Hubble tension: a review of solutions," Class. Quant. Grav. **38** (2021) no.15, 153001 [arXiv:2103.01183 [astro-ph.CO]].

[2] L. Perivolaropoulos and F. Skara, "Challenges for ΛCDM: An update," New Astron. Rev. **95** (2022), 101659 [arXiv:2105.05208 [astro-ph.CO]].

[3] E. Abdalla, G. Franco Abellán, A. Aboubrahim, A. Agnello, O. Akarsu, Y. Akrami, G. Alestas, D. Aloni, L. Amendola and L. A. Anchordoqui, *et al.* "Cosmology intertwined: A review of the particle physics, astrophysics, and cosmology associated with the cosmological tensions and anomalies," JHEAp **34** (2022), 49-211 [arXiv:2203.06142 [astro-ph.CO]].

[4] C. Krishnan, E. Ó Colgáin, M. M. Sheikh-Jabbari and T. Yang, "Running Hubble Tension and a H0 Diagnostic," Phys. Rev. D **103** (2021) no.10, 103509 [arXiv:2011.02858 [astro-ph.CO]].

[5] C. Krishnan and R. Mondol, "H_0 as a Universal FLRW Diagnostic," [arXiv:2201.13384 [astro-ph.CO]].

[6] Ö. Akarsu, E. Ó Colgáin, A. A. Sen and M. M. Sheikh-Jabbari, "ΛCDM Tensions: Localising Missing Physics through Consistency Checks," [arXiv:2402.04767 [astro-ph.CO]].

[7] D. J. Eisenstein *et al.* [SDSS], "Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies," Astrophys. J. **633** (2005), 560-574 [arXiv:astro-ph/0501171 [astro-ph]].

[8] S. Cole *et al.* [2dFGRS], "The 2dF Galaxy Redshift Survey: Power-spectrum analysis of the final dataset and cosmological implications," Mon. Not. Roy. Astron. Soc. **362** (2005), 505-534 [arXiv:astro-ph/0501174 [astro-ph]].

[9] A. G. Adame *et al.* [DESI], "DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations," [arXiv:2404.03002 [astro-ph.CO]].

[10] M. Chevallier and D. Polarski, "Accelerating universes with scaling dark matter," Int. J. Mod. Phys. D **10** (2001), 213-224 [arXiv:gr-qc/0009008 [gr-qc]].

[11] E. V. Linder, "Exploring the expansion history of the universe," Phys. Rev. Lett. **90** (2003), 091301 [arXiv:astro-ph/0208512 [astro-ph]].

[12] N. Aghanim *et al.* [Planck], "Planck 2018 results. VI. Cosmological parameters," Astron. Astrophys. **641** (2020), A6 [erratum: Astron. Astrophys. **652** (2021), C4] [arXiv:1807.06209 [astro-ph.CO]].

[13] D. Brout, D. Scolnic, B. Popovic, A. G. Riess, J. Zuntz, R. Kessler, A. Carr, T. M. Davis, S. Hinton and D. Jones, *et al.* "The Pantheon+ Analysis: Cosmological Constraints," Astrophys. J. **938** (2022) no.2, 110 [arXiv:2202.04077 [astro-ph.CO]].

[14] D. Rubin, G. Aldering, M. Betoule, A. Fruchter, X. Huang, A. G. Kim, C. Lidman, E. Linder, S. Perlmutter and P. Ruiz-Lapuente, *et al.* "Union Through UNITY: Cosmology with 2,000 SNe Using a Unified Bayesian Framework," [arXiv:2311.12098 [astro-ph.CO]].

[15] T. M. C. Abbott *et al.* [DES], "The Dark Energy Survey: Cosmology Results With ~1500 New High-redshift Type Ia Supernovae Using The Full 5-year Dataset," [arXiv:2401.02929 [astro-ph.CO]].

[16] D. Foreman-Mackey, D. W. Hogg, D. Lang and J. Goodman, "emcee: The MCMC Hammer," Publ. Astron. Soc. Pac. **125** (2013), 306-312 [arXiv:1202.3665 [astro-ph.IM]].

[17] E. Ó Colgáin, M. M. Sheikh-Jabbari, R. Solomon, G. Bargiacchi, S. Capozziello, M. G. Dainotti and D. Stojkovic, "Revealing intrinsic flat ΛCDM biases with standardizable candles," Phys. Rev. D **106** (2022) no.4, L041301 [arXiv:2203.10558 [astro-ph.CO]].

[18] S. Alam *et al.* [BOSS], "The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological analysis of the DR12 galaxy sample," Mon. Not. Roy. Astron. Soc. **470** (2017) no.3, 2617-2652 [arXiv:1607.03155 [astro-ph.CO]].

[19] K. C. Wong, S. H. Suyu, G. C. F. Chen, C. E. Rusu, M. Millon, D. Sluse, V. Bonvin, C. D. Fassnacht, S. Taubenberger and M. W. Auger, *et al.* "H0LiCOW – XIII. A 2.4 per cent measurement of H0 from lensed quasars: 5.3σ tension between early- and late-Universe probes," Mon. Not. Roy. Astron. Soc. **498** (2020) no.1, 1420-1439 [arXiv:1907.04869 [astro-ph.CO]].

[20] A. J. Shajib *et al.* [DES], "STRIDES: a 3.9 per cent measurement of the Hubble constant from the strong lens system DES J0408–5354," Mon. Not. Roy. Astron. Soc. **494** (2020) no.4, 6072-6102 [arXiv:1910.06306 [astro-ph.CO]]. [arXiv:2009.06740]]

[21] M. Millon, A. Galan, F. Courbin, T. Treu, S. H. Suyu, X. Ding, S. Birrer, G. C. F. Chen, A. J. Shajib and D. Sluse, *et al.* "TDCOSMO. I. An exploration of systematic uncertainties in the inference of H_0 from time-delay cosmography," Astron. Astrophys. **639** (2020), A101 [arXiv:1912.08027 [astro-ph.CO]].

[22] P. L. Kelly, S. Rodney, T. Treu, M. Oguri, W. Chen, A. Zitrin, S. Birrer, V. Bonvin, L. Dessart and J. M. Diego, *et al.* "Constraints on the Hubble constant from supernova Refsdal's reappearance," Science **380** (2023) no.6649, abh1322 [arXiv:2305.06367 [astro-ph.CO]].

[23] M. Pascale, B. L. Frye, J. D. R. Pierel, W. Chen, P. L. Kelly, S. H. Cohen, R. A. Windhorst, A. G. Riess, P. S. Kamieneski and J. M. Diego, *et al.* "SN H0pe: The First Measurement of H_0 from a Multiply-Imaged Type Ia Supernova, Discovered by JWST," [arXiv:2403.18902 [astro-ph.CO]].

[24] X. Li and K. Liao, "Determining Cosmological-model-independent H_0 with Gravitationally Lensed Supernova Refsdal," [arXiv:2401.12052 [astro-ph.CO]].

[25] M. G. Dainotti, B. De Simone, T. Schiavone, G. Montani, E. Rinaldi and G. Lambiase, "On the Hubble constant tension in the SNe Ia Pantheon sample," Astrophys. J. **912** (2021) no.2, 150 [arXiv:2103.02117 [astro-ph.CO]].

[26] E. Ó Colgáin, M. M. Sheikh-Jabbari, R. Solomon, M. G. Dainotti and D. Stojkovic, "Putting flat ΛCDM in the (Redshift) bin," Phys. Dark Univ. **44** (2024), 101464 [arXiv:2206.11447 [astro-ph.CO]].

[27] X. D. Jia, J. P. Hu and F. Y. Wang, "Evidence of a decreasing trend for the Hubble constant," Astron. Astrophys. **674** (2023), A45 [arXiv:2212.00238 [astro-ph.CO]].

[28] E. Pastén and V. H. Cárdenas, "Testing ΛCDM cosmology in a binned universe: Anomalies in the deceleration parameter," Phys. Dark Univ. **40** (2023), 101224 [arXiv:2301.10740 [astro-ph.CO]].

[29] M. Malekjani, R. M. Conville, E. Ó Colgáin, S. Pourojaghi and M. M. Sheikh-Jabbari, "On redshift evolution and negative dark energy density in Pantheon + Supernovae," Eur. Phys. J. C **84** (2024) no.3, 317 [arXiv:2301.12725 [astro-ph.CO]].

[30] J. Wagner, "Solving the Hubble tension à la Ellis & Stoeger 1987," PoS **CORFU2022** (2023), 267 [arXiv:2203.11219 [astro-ph.CO]].

[31] J. P. Hu and F. Y. Wang, "Revealing the late-time transition of H_0: relieve the Hubble crisis," Mon. Not. Roy. Astron. Soc. **517** (2022) no.1, 576-581 [arXiv:2203.13037 [astro-ph.CO]].

[32] M. Dainotti, B. De Simone, G. Montani;, T. Schiavone; and G. Lambiase., "The Hubble constant tension: current status and future perspectives through new cosmological probes," PoS **CORFU2022** (2023), 235 doi:10.22323/1.436.0235 [arXiv:2301.10572 [astro-ph.CO]].

[33] M. G. Dainotti, B. De Simone, T. Schiavone, G. Montani, E. Rinaldi, G. Lambiase, M. Bogdan and S. Ugale, "On the Evolution of the Hubble Constant with the SNe Ia Pantheon Sample and Baryon Acoustic Oscillations: A Feasibility Study for GRB-Cosmology in 2030," Galaxies **10** (2022) no.1, 24 [arXiv:2201.09848 [astro-ph.CO]].

[34] C. Krishnan, E. Ó Colgáin, Ruchika, A. A. Sen, M. M. Sheikh-Jabbari and T. Yang, "Is there an early Universe solution to Hubble tension?," Phys. Rev. D **102** (2020) no.10, 103525 [arXiv:2002.06044 [astro-ph.CO]].

[35] M. G. Dainotti, G. Sarracino and S. Capozziello, "Gamma-ray bursts, supernovae Ia, and baryon acoustic oscillations: A binned cosmological analysis," Publ. Astron. Soc. Jap. **74** (2022) no.5, 1095-1113-1113 [arXiv:2206.07479 [astro-ph.CO]].

[36] G. Risaliti and E. Lusso, "Cosmological constraints from the Hubble diagram of quasars at high redshifts," Nature Astron. **3** (2019) no.3, 272-277 [arXiv:1811.02590 [astro-ph.CO]].

[37] E. Lusso, G. Risaliti, E. Nardini, G. Bargiacchi, M. Benetti, S. Bisogni, S. Capozziello, F. Civano, L. Eggleston and M. Elvis, *et al.* "Quasars as standard candles III. Validation of a new sample for cosmological studies," Astron. Astrophys. **642** (2020), A150 [arXiv:2008.08586 [astro-ph.GA]].

[38] Dainotti, M.G., Bargiacchi, G., Lenart, A.L., Nagataki, S. and Capozziello, S., ApJ, 950(1), id.45, 8 pp. (2023), Quasars: Standard Candles up to z= 7.5 with the Precision of Supernovae Ia [arXiv:2305.19668, [astro-ph.HE]].

[39] M. G. Dainotti, G. Bargiacchi, A. L. Lenart, S. Capozziello, E. Ó Colgáin, R. Solomon, D. Stojkovic and M. M. Sheikh-Jabbari, "Quasar Standardization: Overcoming Selection Biases and Redshift Evolution," Astrophys. J. **931** (2022) no.2, 106 [arXiv:2203.12914 [astro-ph.HE]].

[40] G. Bargiacchi, M. G. Dainotti, S. Nagataki and S. Capozziello, "Gamma-Ray Bursts, Quasars, Baryonic Acoustic Oscillations,

and Supernovae Ia: new statistical insights and cosmological constraints," doi:10.1093/mnras/stad763 [arXiv:2303.07076 [astro-ph.CO]].

[41] S. Pourojaghi, N. F. Zabihi and M. Malekjani, "Can high-redshift Hubble diagrams rule out the standard model of cosmology in the context of cosmography?," Phys. Rev. D **106** (2022) no.12, 123523 [arXiv:2212.04118 [astro-ph.CO]].

[42] N. Khadka and B. Ratra, "Using quasar X-ray and UV flux measurements to constrain cosmological model parameters," Mon. Not. Roy. Astron. Soc. **497** (2020) no.1, 263-278 [arXiv:2004.09979 [astro-ph.CO]].

[43] N. Khadka and B. Ratra, "Determining the range of validity of quasar X-ray and UV flux measurements for constraining cosmological model parameters," Mon. Not. Roy. Astron. Soc. **502** (2021) no.4, 6140-6156 [arXiv:2012.09291 [astro-ph.CO]].

[44] J. Singal, S. Mutchnick and V. Petrosian, "The X-Ray Luminosity Function Evolution of Quasars and the Correlation between the X-Ray and Ultraviolet Luminosities," Astrophys. J. **932** (2022) no.2, 111 [arXiv:2203.13374 [astro-ph.CO]].

[45] V. Petrosian, J. Singal and S. Mutchnick, "Can the Distance-Redshift Relation be Determined from Correlations between Luminosities?," Astrophys. J. Lett. **935** (2022) no.1, L19 [arXiv:2205.07981 [astro-ph.CO]].

[46] M. Zajaček, B. Czerny, N. Khadka, M. L. Martínez-Aldama, R. Prince, S. Panda and B. Ratra, "Effect of extinction on quasar luminosity distances determined from UV and X-ray flux measurements," [arXiv:2305.08179 [astro-ph.GA]].

[47] Dainotti, M., Biargiacchi, A. Lenart & S. Capozziello "The Scavenger Hunt for Quasar Samples to Be Used as Cosmological Tools", Galaxies, 12, 1, id.4. [arXiv:2401.11998 [astro-ph.CO]].

[48] M. G. Dainotti, A. L. Lenart, M. G. Yengejeh, S. Chakraborty, N. Fraija, E. Di Valentino and G. Montani, "A new binning method to choose a standard set of Quasars," Phys. Dark Univ. **44** (2024), 101428 [arXiv:2401.12847 [astro-ph.HE]].

[49] A. Ł. Lenart, G. Bargiacchi, M. G. Dainotti, S. Nagataki and S. Capozziello, "A Bias-free Cosmological Analysis with Quasars Alleviating H $_0$ Tension," Astrophys. J. Suppl. **264** (2023) no.2, 46 [arXiv:2211.10785 [astro-ph.CO]].

[50] M. Demianski, E. Piedipalumbo, D. Sawant and L. Amati, "Cosmology with gamma-ray bursts: I. The Hubble diagram through the calibrated $E_{\rm p,i}$ - $E_{\rm iso}$ correlation," Astron. Astrophys. **598** (2017), A112 [arXiv:1610.00854 [astro-ph.CO]].

[51] M. Demianski, E. Piedipalumbo, D. Sawant and L. Amati, Astron. Astrophys. **598** (2017), A113 [arXiv:1609.09631 [astro-ph.CO]].

[52] M. G. Dainotti, A. Ł. Lenart, A. Chraya, G. Sarracino, S. Nagataki, N. Fraija, S. Capozziello and M. Bogdan, "The Gamma-ray Bursts fundamental plane correlation as a cosmological tool," [arXiv:2209.08675 [astro-ph.HE]].

[53] N. Khadka, O. Luongo, M. Muccino and B. Ratra, "Do gamma-ray burst measurements provide a useful test of cosmological models?," JCAP **09** (2021), 042 [arXiv:2105.12692 [astro-ph.CO]].

[54] A. C. Alfano, S. Capozziello, O. Luongo and M. Muccino, "Cosmological transition epoch from gamma-ray burst correlations," [arXiv:2402.18967 [astro-ph.CO]].

[55] Dainotti, Cardone, Capozziello, "A time-luminosity correlation for γ-ray bursts in the X-rays", MNRASL, 391, 1, L79. [arXiv:arXiv:0809.1389]

[56] Srinivasaragan et al. "On the Investigation of the Closure Relations for Gamma-Ray Bursts Observed by Swift in the Post-plateau Phase and the GRB Fundamental Plane", ApJ, 903, 1, id.18, 15

[57] A. Aghamousa *et al.* [DESI], "The DESI Experiment Part I: Science, Targeting, and Survey Design," [arXiv:1611.00036 [astro-ph.IM]].

[58] M. G. Dainotti, G. Bargiacchi, M. Bogdan, A. Ł. Lenart, K. Iwasaki, S. Capozziello, B. Zhang and N. Fraija, "Reducing the Uncertainty on the Hubble Constant up to 35% with an Improved Statistical Analysis: Different Best-fit Likelihoods for Type Ia Supernovae, Baryon Acoustic Oscillations, Quasars, and Gamma-Ray Bursts," Astrophys. J. **951** (2023) no.1, 63 [arXiv:2305.10030 [astro-ph.CO]].

[59] A. Lewis, "GetDist: a Python package for analysing Monte Carlo samples," [arXiv:1910.13970 [astro-ph.IM]].

[60] Y. Tada and T. Terada, "Quintessential interpretation of the evolving dark energy in light of DESI," [arXiv:2404.05722 [astro-ph.CO]].

[61] G. Gu, X. Wang, X. Mu, S. Yuan and G. B. Zhao, "Dynamical dark energy in light of cosmic distance measurements I: a demonstration using simulated datasets," [arXiv:2404.06303 [astro-ph.CO]].

[62] X. Wang, G. Gu, X. Mu, S. Yuan and G. B. Zhao, "Dynamical dark energy in light of cosmic distance measurements II: a study using current observations," [arXiv:2404.06310 [astro-ph.CO]].

[63] D. Wang, "Constraining Cosmological Physics with DESI BAO Observations," [arXiv:2404.06796 [astro-ph.CO]].

[64] O. Luongo and M. Muccino, "Model independent cosmographic constraints from DESI 2024," [arXiv:2404.07070 [astro-ph.CO]].

[65] W. Yin, "Cosmic Clues: DESI, Dark Energy, and the Cosmological Constant Problem," [arXiv:2404.06444 [hep-ph]].

[66] E. Ó Colgáin, "A hint of matter underdensity at low z?," JCAP **09** (2019), 006 [arXiv:1903.11743 [astro-ph.CO]].

[67] L. Kazantzidis, H. Koo, S. Nesseris, L. Perivolaropoulos and A. Shafieloo, "Hints for possible low redshift oscillation around the best-fitting ΛCDM model in the expansion history of the Universe," Mon. Not. Roy. Astron. Soc. **501** (2021) no.3, 3421-3426 [arXiv:2010.03491 [astro-ph.CO]].

[68] A. Amon and G. Efstathiou, "A non-linear solution to the S_8 tension?," doi:10.1093/mnras/stac2429 [arXiv:2206.11794 [astro-ph.CO]].

[69] C. Preston, A. Amon and G. Efstathiou, "A non-linear solution to the S8 tension– II. Analysis of DES Year 3 cosmic shear," Mon. Not. Roy. Astron. Soc. **525** (2023) no.4, 5554-5564 [arXiv:2305.09827 [astro-ph.CO]].

[70] R. Terasawa, X. Li, M. Takada, T. Nishimichi, S. Tanaka, S. Sugiyama, T. Kurita, T. Zhang, M. Shirasaki and R. Takahashi, *et al.* "Exploring the baryonic effect signature in the Hyper Suprime-Cam Year 3 cosmic shear two-point correlations on small scales: the S_8 tension remains present," [arXiv:2403.20323 [astro-ph.CO]].

[71] M. Esposito, V. Iršič, M. Costanzi, S. Borgani, A. Saro and M. Viel, "Weighing cosmic structures with clusters of galaxies and the intergalactic medium," Mon. Not. Roy. Astron. Soc. **515** (2022) no.1, 857-870 [arXiv:2202.00974 [astro-ph.CO]].

[72] S. A. Adil, Ö. Akarsu, M. Malekjani, E. Ó Colgáin, S. Pourojaghi, A. A. Sen and M. M. Sheikh-Jabbari, "S_8 increases with effective redshift in ΛCDM cosmology," Mon. Not. Roy. Astron. Soc. **528** (2023) no.1, L20-L26 [arXiv:2303.06928 [astro-ph.CO]].

[73] M. S. Madhavacheril *et al.* [ACT], "The Atacama Cosmology Telescope: DR6 Gravitational Lensing Map and Cosmological Parameters," Astrophys. J. **962** (2024) no.2, 113 [arXiv:2304.05203 [astro-ph.CO]].

[74] I. Tutusaus, C. Bonvin and N. Grimm, "First measurement of the Weyl potential evolution from the Year 3 Dark Energy Sur-

vey data: Localising the σ_8 tension," [arXiv:2312.06434 [astro-ph.CO]].