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A Sound Horizon-Free Measurement of H_0 in DESI 2024

E. A. Zaborowski^{1,2,3} P. Taylor,³ K. Honscheid^{1,2,3} A. Cuceu^{1,4}
A. de Mattia⁵ D. Huterer^{6,7} A. Krolewski,^{8,9,10} P. Martini^{1,11,3}
A. J. Ross^{1,11,3} C. To,³ A. Torres,³ S. Ahlen¹² D. Bianchi¹³
D. Brooks,¹⁴ E. Buckley-Geer,^{15,16} E. Burtin,⁵ T. Claybaugh,⁴
S. Cole¹⁷ A. de la Macorra¹⁸ Arjun Dey¹⁹
Biprateep Dey^{20,21} P. Doel,¹⁴ S. Ferraro^{4,22}
A. Font-Ribera^{14,23} J. E. Forero-Romero^{24,25}
E. Gaztañaga,^{26,27,28} H. Gil-Marín^{29,26,30} G. Gutierrez,¹⁶ J. Guy⁴
C. Hahn³¹ C. Howlett³² S. Juneau,¹⁹ R. Kehoe,³³
D. Kirkby³⁴ T. Kisner⁴ A. Kremin⁴ M. Landriau⁴
L. Le Guillou³⁵ M. E. Levi⁴ C. Magneville,⁵ A. Meisner¹⁹
R. Miquel,^{36,23} J. Moustakas³⁷ N. Palanque-Delabrouille^{5,4}
W. J. Percival^{8,9,10} F. Prada³⁸ I. Pérez-Ràfols³⁹ G. Rossi,⁴⁰
E. Sanchez⁴¹ D. Schlegel,⁴ M. Schubnell,^{6,7} H. Seo⁴²
D. Sprayberry,¹⁹ G. Tarlé⁷ B. A. Weaver,¹⁹
R. H. Wechsler^{43,44,45}

¹Center for Cosmology and AstroParticle Physics, The Ohio State University, 191 West Woodruff Avenue, Columbus, OH 43210, USA

²Department of Physics, The Ohio State University, 191 West Woodruff Avenue, Columbus, OH 43210, USA

³The Ohio State University, Columbus, 43210 OH, USA

⁴Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA

⁵IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

⁶Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA

⁷University of Michigan, Ann Arbor, MI 48109, USA

⁸Department of Physics and Astronomy, University of Waterloo, 200 University Ave W, Waterloo, ON N2L 3G1, Canada

⁹Perimeter Institute for Theoretical Physics, 31 Caroline St. North, Waterloo, ON N2L 2Y5, Canada

¹⁰Waterloo Centre for Astrophysics, University of Waterloo, 200 University Ave W, Waterloo, ON N2L 3G1, Canada

¹¹Department of Astronomy, The Ohio State University, 4055 McPherson Laboratory, 140 W 18th Avenue, Columbus, OH 43210, USA

- ¹²Physics Dept., Boston University, 590 Commonwealth Avenue, Boston, MA 02215, USA
- ¹³Dipartimento di Fisica “Aldo Pontremoli”, Università degli Studi di Milano, Via Celoria 16, I-20133 Milano, Italy
- ¹⁴Department of Physics & Astronomy, University College London, Gower Street, London, WC1E 6BT, UK
- ¹⁵Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA
- ¹⁶Fermi National Accelerator Laboratory, PO Box 500, Batavia, IL 60510, USA
- ¹⁷Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham DH1 3LE, UK
- ¹⁸Instituto de Física, Universidad Nacional Autónoma de México, Circuito de la Investigación Científica, Ciudad Universitaria, Cd. de México C. P. 04510, México
- ¹⁹NSF NOIRLab, 950 N. Cherry Ave., Tucson, AZ 85719, USA
- ²⁰Department of Astronomy & Astrophysics, University of Toronto, Toronto, ON M5S 3H4, Canada
- ²¹Department of Physics & Astronomy and Pittsburgh Particle Physics, Astrophysics, and Cosmology Center (PITT PACC), University of Pittsburgh, 3941 O’Hara Street, Pittsburgh, PA 15260, USA
- ²²University of California, Berkeley, 110 Sproul Hall #5800 Berkeley, CA 94720, USA
- ²³Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra Barcelona, Spain
- ²⁴Departamento de Física, Universidad de los Andes, Cra. 1 No. 18A-10, Edificio Ip, CP 111711, Bogotá, Colombia
- ²⁵Observatorio Astronómico, Universidad de los Andes, Cra. 1 No. 18A-10, Edificio H, CP 111711 Bogotá, Colombia
- ²⁶Institut d’Estudis Espacials de Catalunya (IEEC), 08034 Barcelona, Spain
- ²⁷Institute of Cosmology and Gravitation, University of Portsmouth, Dennis Sciama Building, Portsmouth, PO1 3FX, UK
- ²⁸Institute of Space Sciences, ICE-CSIC, Campus UAB, Carrer de Can Magrans s/n, 08913 Bellaterra, Barcelona, Spain
- ²⁹Departament de Física Quàntica i Astrofísica, Universitat de Barcelona, Martí i Franquès 1, E08028 Barcelona, Spain
- ³⁰Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (UB), c. Martí i Franquès, 1, 08028 Barcelona, Spain.
- ³¹Department of Astrophysical Sciences, Princeton University, Princeton NJ 08544, USA
- ³²School of Mathematics and Physics, University of Queensland, 4072, Australia
- ³³Department of Physics, Southern Methodist University, 3215 Daniel Avenue, Dallas, TX 75275, USA
- ³⁴Department of Physics and Astronomy, University of California, Irvine, 92697, USA
- ³⁵Sorbonne Université, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), FR-75005 Paris, France
- ³⁶Institució Catalana de Recerca i Estudis Avançats, Passeig de Lluís Companys, 23, 08010 Barcelona, Spain
- ³⁷Department of Physics and Astronomy, Siena College, 515 Loudon Road, Loudonville, NY 12211, USA

³⁸Instituto de Astrofísica de Andalucía (CSIC), Glorieta de la Astronomía, s/n, E-18008 Granada, Spain

³⁹Departament de Física, EEBE, Universitat Politècnica de Catalunya, c/Eduard Maristany 10, 08930 Barcelona, Spain

⁴⁰Department of Physics and Astronomy, Sejong University, Seoul, 143-747, Korea

⁴¹CIEMAT, Avenida Complutense 40, E-28040 Madrid, Spain

⁴²Department of Physics & Astronomy, Ohio University, Athens, OH 45701, USA

⁴³Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Menlo Park, CA 94305, USA

⁴⁴Physics Department, Stanford University, Stanford, CA 93405, USA

⁴⁵SLAC National Accelerator Laboratory, Menlo Park, CA 94305, USA

E-mail: zaborowski.11@osu.edu

Abstract. The physical size of the sound horizon at recombination is a powerful source of information for early-time measurements of the Hubble constant H_0 , and many proposed solutions to the Hubble tension therefore involve modifications to this scale. In light of this, there has been growing interest in measuring H_0 independently of the sound horizon. We present the first such measurement to use data from the Dark Energy Spectroscopic Instrument (DESI), jointly analyzing the full-shape galaxy power spectra of DESI luminous red galaxies, emission line galaxies, quasars, and the bright galaxy sample, in a total of six redshift bins. Information from the sound horizon scale is removed from our constraints via a rescaling procedure at the power spectrum level, with our sound horizon-marginalized measurement being driven instead primarily by the matter-radiation equality scale. This measurement is then combined with additional sound horizon-free information from *Planck*+ACT CMB lensing, uncalibrated type Ia supernovae, and the DESI Lyman- α forest. We agnostically combine with the DESY5, Pantheon+, and Union3 supernova datasets, with our tightest respective constraints being $H_0 = 66.7^{+1.7}_{-1.9}$, $67.9^{+1.9}_{-2.1}$, and $67.8^{+2.0}_{-2.2}$ km s $^{-1}$ Mpc $^{-1}$. This corresponds to a sub-3% sound horizon-free constraint of the Hubble constant, and is the most precise measurement of its kind to date. Even without including information from the sound horizon, our measurement is still in 2.2-3.0 σ tension with SH0ES. Additionally, the consistency between our result and other measurements that *do* rely on the sound horizon scale provides no evidence for new early-Universe physics (e.g. early dark energy). Future DESI data releases will allow unprecedented measurements of H_0 and place strong constraints on models that use beyond- Λ CDM physics to ameliorate the Hubble tension.

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1 Introduction

The Hubble tension (see [1] for a review) is one of the most pressing issues in cosmology. The Hubble constant H_0 parameterizes the expansion rate of the Universe, and in particular there is a $\sim 5\sigma$ discrepancy between the local distance ladder measurement of H_0 by the SH0ES collaboration [2], and the measurement reported by the *Planck* collaboration [3] using the cosmic microwave background (CMB). This difference could arise either because of unrealized systematic errors in one or both measurements, or due to new physics beyond the standard Λ Cold Dark Matter (Λ CDM) model of cosmology (see [4] for an extensive review of possible solutions to the Hubble tension, including systematics). Many high-redshift/early-time H_0 constraints, such as those from the CMB (e.g. [3, 5]) or from baryon acoustic oscillations (BAO; e.g. [6–11]), derive a significant amount of information from the physics of recombination and the sound horizon distance at the time of recombination.¹ The sound horizon is a standard ruler that, once calibrated, can be used to infer H_0 from the relevant

¹We note that there is a subtle distinction between the sound horizon distance at photon decoupling (r_s , which sources features in the CMB), and the sound horizon distance at baryon decoupling (r_d , which sources baryonic features in the matter power spectrum) [12, 13]. Where the distinction is not important we refer simply to the “sound horizon.”

features in these datasets (see Section 2). Because of this, many solutions to the Hubble tension that rely on modifications to physics to decrease the physical size of the sound horizon have been proposed [14]. This includes, among others: early dark energy (EDE) [15–17], additional light degrees of freedom [18, 19] or new interactions between them [20–22], and reduction of the sound speed in the photon-baryon plasma prior to decoupling [14].

For this reason, there has been growing interest in measuring H_0 independently of the sound horizon scale [23–26]. In [23] it was proposed to measure H_0 using the gravitational lensing of the CMB, which is not sensitive to the sound horizon scale, but rather to the wavenumber k_{eq} corresponding to the comoving horizon size at the epoch of matter-radiation equality (see Section 2). The precision of this measurement can then be improved by combining with additional information on the matter density Ω_m , which they sourced from uncalibrated type Ia supernovae (SNe Ia). A recent application of this method by [27] using CMB lensing data from the Atacama Cosmology Telescope (ACT; [28, 29]) and *Planck* [30–33], combined with galaxies from the unWISE catalog [34] and uncalibrated supernovae from the Pantheon+ dataset [35], resulted in a precise sound horizon-free measurement of $H_0 = 64.3_{-2.4}^{+2.1} \text{ km s}^{-1} \text{ Mpc}^{-1}$. Others have measured H_0 without the sound horizon through a direct measurement of k_{eq} , via the turnover scale of the matter power spectrum [36]. In [37], a similar measurement of the horizon size at matter-radiation equality was proposed via the zero-crossing scale of the matter correlation function. Recently, [38] demonstrated that H_0 can be derived from measurements of cosmological energy densities without including information from the sound horizon scale.

Galaxy surveys provide one of the most promising avenues to measure H_0 without the sound horizon. As remarked in [24], a 3D galaxy survey can typically probe a much larger number of modes than CMB lensing, and ongoing and upcoming surveys (e.g. the Dark Energy Spectroscopic Instrument (DESI; [39–41]), Euclid [42], the Nancy Grace Roman Space Telescope [43], and SPHEREx [44]) are pushing to ever-larger volumes. In [24], using galaxy power spectrum measurements from the completed Baryon Oscillation Spectroscopic Survey (BOSS DR12; [45, 46]), the authors obtained a measurement of the Hubble constant without the sound horizon by using an uninformative prior on the physical baryon density $\omega_b \equiv \Omega_b h^2$. This method has the benefit of simplicity and leaves the physical size of the sound horizon uncalibrated, but as we explain in Section 2, ω_b also contributes to multiple physical effects that constrain H_0 , and removing this information is not ideal. In [47], a technique was demonstrated to rescale and marginalize over the sound horizon scale during inference, thus allowing the use of an informative ω_b prior while removing information from the sound horizon scale. Building on this technique, [48] obtained a 3.6% measurement of the Hubble constant by combining BOSS power spectra with *Planck* CMB lensing and SNe Ia from the Pantheon+ dataset.

In this work, we perform a similar (but blind) measurement to that of [48], using data from the first public data release of the Dark Energy Spectroscopic Instrument (DESI 2024; [49]). We note that we performed our analysis “blind” in the sense that we only tested our pipeline using mocks before finally running on real data. We combine our result with CMB lensing data from ACT [28, 29] and *Planck* [30–33]. We further increase the precision of our measurement by including additional Ω_m information from two sources: the Alcock-Paczyński (AP) effect [50] observed in the DESI 3D Lyman- α (Ly α) forest [51], and uncalibrated type Ia supernovae. This work represents the most precise measurement of its kind to date, achieving a sub-3% sound horizon-free measurement of H_0 . The remainder of this paper is laid out as follows. In Section 2 we discuss how each dataset used in this work helps to constrain

the Hubble constant without including information from the sound horizon scale, and then in Section 3 we describe each specific dataset in detail. In Section 4 we describe the steps and components of our analysis pipeline. We present the results of our analysis in Section 5, followed by a discussion in Section 6. Finally, we conclude in Section 7.

2 Theory and Methodology

The galaxy power spectrum contains multiple sources of information that contribute to measuring H_0 . On one hand there is geometrical information; one form that this takes is in so-called “standard rulers,” or features of the power spectrum that correspond to theoretically known distance scales. This includes the sound horizon scale at baryon-photon decoupling r_d , which determines the structure of the BAO wiggles, as well as the baryonic Jeans suppression scale [52]. Another standard ruler is the matter-radiation equality scale k_{eq} , which manifests as the turnover scale of the power spectrum and also modulates its shape around the peak.² The observed scale (in angles/redshifts) of a given standard ruler is then a function of both its physical size as well as the distance to the tracer it is measured from, both of which are predicted by a cosmological model. This leads to a measurement of the relevant cosmological parameters (or combinations thereof), including the Hubble constant. Further geometrical information is gained by jointly analyzing tracers at multiple redshifts. Because $k_{\text{eq}} \propto \Omega_m h$ (when measured in $h \text{ Mpc}^{-1}$ units; see Equation 2.2), constraints based on the matter-radiation equality scale k_{eq} display a characteristic degeneracy in the $\Omega_m - h$ plane. However, because we observe power spectrum features in angles ($\theta_{\text{eq}} \sim \ell_{\text{eq}}^{-1} \sim (D_A(z) k_{\text{eq}})^{-1}$) and redshifts ($\Delta z_{\text{eq}} \sim H(z)/k_{\text{eq}}$) rather than physical distances, this degeneracy direction varies with redshift according to the assumed fiducial cosmological model. The resulting constraints, while largely degenerate for any individual tracer, then intersect at different angles, resulting in a more precise joint constraint. A similar phenomenon arises in BAO analyses (see for example Figure 2 of [11]).

Somewhat related to geometrical information is the Alcock-Paczyński (AP) effect [50]. When a fiducial cosmology is used to transform galaxy positions from redshift space (R.A., Dec., z) to Cartesian space (x, y, z), any difference between the assumed cosmology and true cosmology will cause clustering features to appear stretched along/across the line of sight. This fictitious distortion is known as the AP effect, and can be related to the true matter density Ω_m (e.g. [51]). Importantly, the AP distortion is independent of absolute distance scales, and thus we can use it to help to break the $\Omega_m - H_0$ degeneracy alluded to earlier. Measuring the AP effect requires modelling the full anisotropic contribution to the clustering signal, known as redshift space distortions (RSD), where the latter are also induced by peculiar velocities related to the growth of structure. Because of its dependence on the peculiar velocity field, the RSD measurement can be used to obtain information about the amplitude of the power spectrum, which also has some degeneracy with the Hubble constant (see Section 5). Beyond geometric sources, the AP effect, and RSD, note that there is still additional information contained in the shape of the power spectrum. For example, [38] demonstrated a method to derive H_0 using energy density measurements, making use of (among other measurements) the amplitude of the BAO signal from galaxy clustering while marginalizing over the physical sound horizon scale.

²As discussed in [24], k_{eq} appears non-trivially in the shape of the logarithmic enhancement on scales $k > k_{\text{eq}}$.

Because we want to capture as much information as possible, we choose to analyze the entire shape of power spectrum, rather than any single feature. To do this we use a **Full Modeling** approach (adopting the terminology of [53]), in which we directly generate model power spectrum multipoles from cosmological parameters and fit them to the observed data. This is in contrast to compression-based approaches, in which compressed parameters are fit to the data in a more model-independent way. A ubiquitous example of this is the α_{\parallel} , α_{\perp} (or α_{iso} , α_{AP}) parameterization used in BAO analyses (e.g. [9]). Recently, there have been extensions of this approach to full-shape analyses, e.g. **ShapeFit** [54], which uses a template power spectrum to fit for individual effects (RSD, Alcock-Paczyński, etc.) with respect to the fiducial cosmology (see e.g. [25] for a precise sound horizon-independent measurement of H_0 using the ShapeFit approach). While the Full Modeling approach is more computationally expensive, it captures all of the available information without compression (see e.g. [55–57] for comparisons of Full Modeling and compression/template-based techniques).

In Λ CDM the sound horizon at the redshift of baryon-photon decoupling z_d (also known as the baryon drag epoch) is given by:

$$r_d \equiv \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz \approx \frac{55.154h \exp \left[-72.3 (\omega_{\nu} + 0.0006)^2 \right]}{\omega_{\text{cb}}^{0.25351} \omega_{\text{b}}^{0.12807}} [h^{-1} \text{Mpc}] \quad (2.1)$$

[58], where c_s is the speed of sound in the photon-baryon plasma prior to decoupling, and $\omega_{\text{cb}} \equiv \omega_{\text{cdm}} + \omega_{\text{b}}$. On the other hand, the matter-radiation equality scale can be calculated as:

$$k_{\text{eq}} = (2\Omega_{\text{cb}} H_0^2 z_{\text{eq}})^{1/2} \approx 7.46 \times 10^{-2} \Omega_{\text{cb}} h \Theta_{2.7}^{-2} [h \text{Mpc}^{-1}] \quad (2.2)$$

[13], where $\Theta_{2.7} \equiv T_{\text{CMB}}/(2.7 \text{K})$. Naturally, the full shape of the power spectrum contains information from both scales, and we would like to remove the sound horizon information from our measurement. In [24], it was shown that this can be accomplished simply by performing a Full Modeling analysis with an uninformative prior on ω_{b} . In this way, the physical size of the sound horizon remains uncalibrated,³ and thus cannot be used as a standard ruler in the measurement of H_0 . However, this method has the disadvantage of weakening other sources of H_0 information that also depend on the baryon density, e.g. the matter-radiation equality scale, or the critical density of the Universe (in the sense of [38]). An improved method, demonstrated in [47] and subsequently used in [48], heuristically rescales and marginalizes over r_d while still allowing the use of an informative prior on ω_{b} . We adopt this approach, which we describe below.

We first split the linear power spectrum into a smooth and wiggly component. To accomplish this, we use a simple version⁴ of the method described in Appendix D of [59] to obtain the smooth part of the power spectrum, where the wiggly part can then be obtained as the difference between the original power spectrum and the smooth part. We refer the reader to the given reference for details of the method; here we give only a brief summary. The

³The authors noted that in principle, r_d can be self-calibrated from the combination of the BAO wiggles and the baryonic Jeans suppression scale, but this was not a strong enough prior at the precision of BOSS. In [47] the authors further demonstrated that this effect is not expected to be significant even for a Euclid-like survey.

⁴https://github.com/cosmodesi/cosmoprime/blob/main/cosmoprime/bao_filter.py#L472

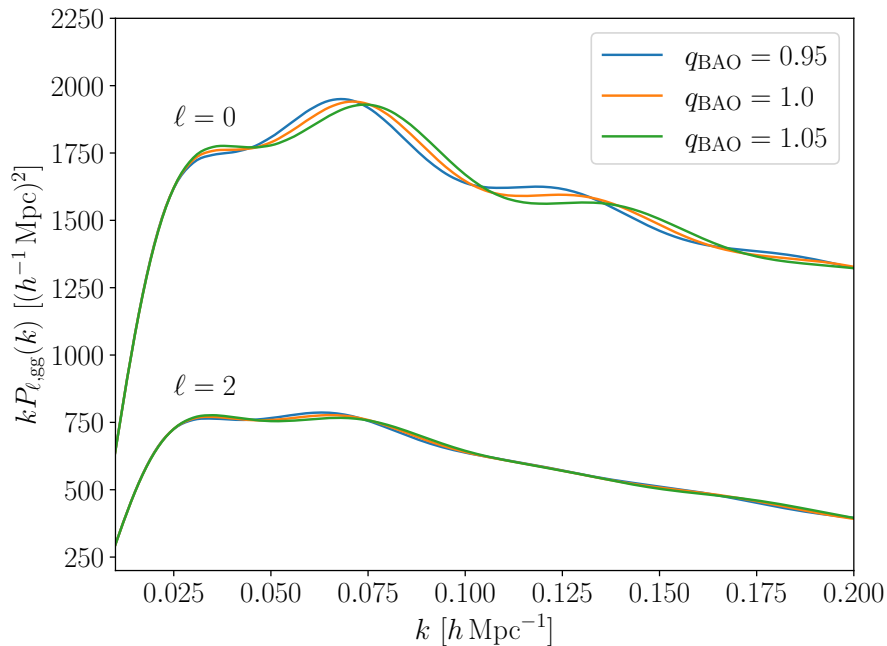


Figure 1. A visual demonstration of the heuristic sound horizon rescaling technique used in this work. Adopting the methodology developed in [47], we rescale the power spectrum wiggles by a free parameter q_{BAO} . Shown above are the monopole ($\ell = 0$) and quadrupole ($\ell = 2$) of the theoretical galaxy power spectrum of DESI LRGs in the redshift range $0.4 < z < 0.6$, for three values of q_{BAO} . $q_{\text{BAO}} = 1.0$ corresponds to the ΛCDM prediction (no rescaling of the sound horizon), whereas $q_{\text{BAO}} = 1.05$ and $q_{\text{BAO}} = 0.95$ have the effect of moving the wiggles forward and backward, respectively.

broadband shape of the power spectrum is first divided out using the smooth Eisenstein-Hu formula [13], resulting in an approximation of the wiggles. Then, the gradient of the latter is calculated numerically and extremized. The maxima and minima thus obtained correspond to the nodes of the wiggles; importantly, the smooth part must also pass through these nodes. Two smooth functions are fit using quadratic splines: one each crossing the nodes that correspond to the gradient maxima or minima, and these curves are finally averaged to give the smooth part of the power spectrum.

Once the smooth and wiggly components have been separated using the above technique, we rescale only the wiggly part by a new parameter q_{BAO} (called α_{r_s} in [47]). We then recombine the two components, such that the transformed linear power spectrum can be described as:

$$P_{\text{lin}}(k, q_{\text{BAO}}) = P_{\text{lin}}^{\text{smooth}}(k) + P_{\text{lin}}^{\text{wiggly}}(q_{\text{BAO}} \cdot k) \quad (2.3)$$

We can then use this modified linear power spectrum as an input to our full non-linear galaxy clustering model, described in Section 4.3. Roughly speaking, the effect of this heuristic transformation is to rescale r_d by a factor q_{BAO}^{-1} , phenomenologically capturing any modifications to the physics that determines the scale of this feature. In Fig. 1 we show visually the rescaling of the galaxy power spectrum monopole and quadrupole for three values of q_{BAO} . Note that $q_{\text{BAO}} = 1.0$ corresponds to ΛCDM (no rescaling), while larger (smaller) values of q_{BAO}

shift the BAO wiggles forward (backward). By allowing q_{BAO} to vary freely, the information from the sound horizon scale is marginalized over during inference. We note that several tests were performed in [47] and [48] to demonstrate that the constraints obtained from this procedure are indeed independent of sound horizon information, at least at the precision of DESI and Euclid.

As mentioned earlier, the CMB lensing power spectrum is also sensitive to the matter-radiation equality scale. As discussed in [23], the projection integral relating the lensing power spectrum to the intervening matter power spectrum has the effect of washing out sharp features such as the BAO wiggles. Because of this, CMB lensing is not sensitive to the sound horizon scale,⁵ but rather to the broadband shape of the matter power spectrum, which is modulated by the matter-radiation equality scale as noted above. Thus CMB lensing constrains H_0 similarly to above, albeit with a distinct degeneracy direction in the $\Omega_m - H_0$ plane, helping to improve the joint constraint.

Clearly, the $\Omega_m - H_0$ degeneracy can be broken further by including additional information on Ω_m . In this work we consider two additional sources of Ω_m information. The first of these is type Ia supernovae (SNe Ia). SNe Ia are standardizable candles that trace the expansion history of the Universe. When the local distance ladder [2, 60] is used to calibrate the absolute magnitudes of SNe Ia, their observed brightnesses imply physical distances, and they can be used to measure H_0 . When left uncalibrated they no longer provide absolute distance information, but still probe the expansion history. In a flat universe and for a fixed dark energy equation of state, this primarily provides information on Ω_m . The second source of Ω_m information we include in our measurement is the AP effect observed in the full-shape 3D Lyman- α forest power spectrum [51, 61, 62]. As mentioned above, information from the AP effect is also included in galaxy clustering, however the effect is stronger for the Ly α forest as it is more sensitive to small-scale structures [61]. The Ly α forest [63, 64] can be seen in the spectra of distant quasars, and traces the density of the intervening neutral hydrogen. As light travels toward us from a quasar and becomes redshifted by the expansion of space, it can be absorbed by neutral hydrogen (in this case as Ly α photons). Thus we observe a “forest” of absorption lines in the quasar spectrum, blueward of the quasar’s rest-frame Ly α wavelength. By considering the emitted wavelength of the quasar light and the strength of its absorption, the structure of the intervening neutral hydrogen can be inferred. The AP distortion observed in the Ly α forest power spectrum then provides information on Ω_m , as discussed previously.

3 Data

Here we describe each specific dataset used in this work.

3.1 Galaxies and the Lyman- α Forest

The Dark Energy Spectroscopic Instrument (DESI) is a multi-object spectrographic survey performed using $\sim 5,000$ robotically positioned fibers and operating on the Mayall 4-meter telescope at Kitt Peak National Observatory [40, 65–67]. DESI is currently conducting a five-year survey that will cover roughly $14,000 \text{ deg}^2$ of the sky and obtain the spectra of more than 40 million galaxies and quasars [39]. The main science goal of the survey is to probe the nature of dark energy via the most precise measurement of the expansion history of the

⁵In [23], the authors additionally verify that no significant information is sourced from the baryonic Jeans suppression scale.

Universe to date [68]. The spectroscopic data reduction pipeline used for DESI is described in [69], while the survey operations and observation plan are detailed in [70]. DESI target selection is based on imaging data from the public DESI Legacy Imaging Surveys [71]. The DESI scientific program was validated in [41], accompanied by an early data release [72].

The first-year data release of the DESI survey (DESI 2024; [49]) contains the positions and spectra of over 5.7 million unique objects, which are classified among several tracers in multiple redshift bins. Accompanying the DESI 2024 data release are several science Key Papers: two-point clustering measurements and validation [73], measurements of the BAO feature in galaxies and quasars [9] and the Lyman- α ($\text{Ly}\alpha$) forest [10], and the full-shape study of galaxies and quasars [74]. Cosmological interpretations were given for the BAO measurements [11] and the full-shape analysis [53]. In this work we jointly analyze the full-shape clustering of a total of six unique tracer/redshift combinations in DESI 2024: the low-redshift bright galaxy sample (BGS) at redshift range $0.1 < z < 0.4$, luminous red galaxies (LRGs) in three redshift bins ($0.4 < z < 0.6$, $0.6 < z < 0.8$, and $0.8 < z < 1.1$), emission line galaxies (ELGs) in the redshift range $1.1 < z < 1.6$, and quasars (quasi-stellar objects or QSOs) in the redshift range $0.8 < z < 2.1$, together comprising a total of 4.7 million galaxies. Additionally, we make use of measurements of the $\text{Ly}\alpha$ forest, as observed in the spectra of distant DESI quasars. In particular, we use the measurement by [51] of the Alcock-Paczynski effect observed in the 3D power spectrum of the DESI $\text{Ly}\alpha$ forest.

3.2 CMB Lensing

We use a combination of CMB lensing data from the *Planck* [3] and ACT [5, 75] surveys. Specifically, we use the *Planck* NPIPE PR4 lensing reconstruction [33], which covers $\sim 27,600$ deg² of the sky, and the ACT DR6 lensing reconstruction [5, 75], covering 9,400 deg². We make use of the publicly available⁶ *Planck*+ACT CMB-marginalized lensing-only likelihood.

3.3 Type Ia Supernovae

As in [11] and [53], we combine our results with three separate uncalibrated supernova datasets. Because uncalibrated SNe Ia primarily constrain Ω_m (as was noted in Section 2), we choose to extract Ω_m priors from each dataset rather than working with the full posteriors, which would provide little additional information. We perform the combination with each supernova dataset individually, without favoring any one over the other. These datasets are the Dark Energy Survey Year 5 supernova analysis (DESY5; [76]), Pantheon+ [77], and Union3 [78]. We very briefly describe each dataset, referring the reader to the relevant references for further information. DESY5 represents the largest and most homogeneous single sample of high-redshift supernovae to date; it combines novel observations of 1,635 photometrically classified SNe Ia (spanning $0.1 < z < 1.3$) with existing observations of 194 low-redshift ($0.025 < z < 0.1$) SNe Ia, the latter of which are also shared by Pantheon+. The Pantheon+ dataset itself is a compilation of data from many surveys; it contains four separate high-redshift samples ($z > 1.0$), three mid-redshift samples ($0.1 < z < 1.0$), and 11 different low-redshift samples ($z < 0.1$), for a total of 1,550 spectroscopically confirmed SNe Ia. Union3 consists of 2,087 SNe Ia, sharing 1,363 with Pantheon+, and additionally makes use of a Bayesian Hierarchical Modeling approach in its likelihood analysis.

⁶https://github.com/ACTCollaboration/act_dr6_lenslike. We enforced the following settings for our analysis: `variant = actplanck.baseline` and `lens_only = true`.

4 Likelihood and Analysis

Here we describe the settings and techniques used in our analysis. The entire analysis pipeline is built into the code `desilike`.⁷ Throughout this work we assume a cosmology with $\tau_{\text{reio}} = 0.0544$, $N_{\text{eff}} = 3.046$, and three degenerate species of massive neutrinos.

4.1 Data Vector

We filter the galaxy power spectrum multipoles measured in DESI 2024 for each tracer to wavenumber k in the range $[0.02, 0.20] h \text{ Mpc}^{-1}$ for $\ell = 0, 2$, in steps $dk = 0.005 h \text{ Mpc}^{-1}$. This is consistent with the analyses of [53, 74], however we note that the k -range of our data vector does not include the expected turnover scale of the power spectrum, $k_{\text{eq}} \sim 0.015 h \text{ Mpc}^{-1}$. As remarked in Section 2, the matter-radiation equality scale not only sets the turnover scale of the power spectrum, but also appears non-trivially in its broadband shape. In fact, [26] showed that for data from BOSS, the scales $k > k_{\text{eq}}$ are dominant over the position of the turnover scale in constraining H_0 without the sound horizon. We expect this also to be the case for the first DESI data release, but this may change in the future as the peak of the power spectrum becomes better resolved.

All additional processing of the data, including truncation of small angular scales [79], “rotation” of the data vector to compactify the window matrix in k -space [79], and corrections for the radial integral constraint (RIC) [80] and angular integral constraint (AIC) [73], directly follows the methodology described in [73]. The latter two effects (the RIC and AIC) are particularly important to account for in this analysis, as they lead to the damping of power on large radial and angular scales, respectively. In summary, the RIC arises because the redshift distribution of randoms exactly matches that of the data (by design), while the AIC is caused by the use of imaging systematic weights that are obtained by regressing the galaxy density on several maps that encode various imaging properties. Both effects are individually corrected by comparing the mean power spectra of mocks that do/do not contain the particular effect, and fitting a polynomial to capture the difference in power.

4.2 Covariance Matrix

We use a covariance matrix that is a sum of both a statistical and systematic component. The statistical part of the covariance matrix is described in detail in [81], whereas the systematic contributions are given in [74], with the detailed methodology of their combination shown in Appendix D of the latter. The statistical part of covariance matrix was calculated using 1,000 EZmocks (effective Zel’dovich approximation mocks, [82]), which are faster to create than full N -body simulations, while still accurately capturing the DESI 2024 clustering statistics. As discussed in [74], any systematic effect that leads to a parameter-level bias of at least 0.2σ (in units of the DESI 2024 error) is included in the systematic component of the covariance matrix. These systematic contributions include imaging effects, fiber assignment, and halo occupation distribution (HOD)-dependent systematics. Once added in quadrature, these effects contribute a systematic uncertainty of $\sim 0.46\sigma$ in units of the DESI 2024 error, which is much smaller than the sound horizon-marginalized error level of this work.

⁷<https://desilike.readthedocs.io>

4.3 Power Spectrum Model

To calculate the theoretical galaxy power spectrum, we use the publicly available code `velocileptors`⁸ [83, 84], which is based on the effective field theory of large-scale structure (EFT of LSS). We use the Lagrangian perturbation theory (LPT) implementation up to third order, fixing the third-order bias parameter b_3 to zero similarly to [53, 74]. We adopt a physically motivated reparameterization of the EFT biases, counterterms, and stochastic terms, which is outlined in [74]. By using this parameterization, physically interpretable priors can be enforced on these parameters, as discussed in Section 4.4.

4.4 Priors

Our prior choices largely follow [53, 74], and we summarize them below while noting any differences. The baseline Bayesian priors used in this work (that is, for constraints from the DESI data alone) are shown in Table 1. In summary, we sample the cosmological parameters H_0 , Ω_m , ω_b , $\ln(10^{10} A_s)$, n_s , and q_{BAO} , as well as bias parameters in the basis $(1 + b_1) \sigma_8$, $b_2 \sigma_8^2$, $b_s \sigma_8^2$ (chosen to reduce projection effects, described below), while enforcing a maximization procedure on the counterterms $\alpha_{[0,2,4]}$ and stochastic parameters $\text{SN}_{[0,2,4]}$ that efficiently approximates a Jeffreys prior [85, 86]. We note that we sample the parameter Ω_m instead of ω_{cdm} as in [53, 74], and we also allow the nuisance parameters α_4 and SN_4 to vary rather than fixing them to zero (the latter corresponds to an older analysis configuration and will cause our parameter errors to be slightly more conservative). Additionally, use of the Jeffreys prior is unique to this work, and we discuss it in depth at the end of this section. We fix the sum of the neutrino masses, $\sum m_\nu$, to 0.06 eV.⁹ We include two external priors: a Big Bang Nucleosynthesis (BBN) prior on ω_b [88], and a wide Gaussian prior on n_s with standard deviation 0.042, corresponding to $10\times$ the width of the posterior reported by the *Planck* collaboration using both the primary CMB fluctuations and their gravitational lensing by large-scale structure (TT,TE,EE+lowE+lensing) [3]. When combining our results with CMB lensing, we enforce the narrower n_s prior employed in the *Planck* lensing-only analysis: $n_s \sim \mathcal{N}(0.96, 0.02^2)$ [32]. We enforce Gaussian priors on the EFT counterterms $\alpha_{[0,2,4]}$ such that the 1σ correction to the power spectrum at $k_{\text{max}} = 0.2 h \text{Mpc}^{-1}$ is at most 50% of the total signal; this translates to a $\mathcal{N}(0, 12.5^2)$ prior [74]. For the stochastic terms, we enforce a Gaussian prior $\mathcal{N}(0, 2^2) \times 1/\bar{n}_g$ on the monopole term SN_0 , corresponding to a width of $2\times$ the Poissonian shot noise, and $\mathcal{N}(0, 5^2) \times f_{\text{sat}} \sigma_{1\text{eff}}^2 / \bar{n}$ for SN_2 , corresponding to a width of $5\times$ the characteristic velocity dispersion, where f_{sat} is the expected satellite galaxy fraction and $\sigma_{1\text{eff}}^2$ is the velocity dispersion of these galaxies. SN_4 uses a prior with the same width as SN_2 , but with an additional factor of $\sigma_{1\text{eff}}^2$.

As mentioned above, we differ from [53, 74] in applying an approximate Jeffreys prior [85] to a subset of the parameters comprised by the counterterms and stochastic terms. Bayesian inference using EFT models, which have a very high-dimensional space of nuisance parameters, is generally prone to parameter biases due to what are known as prior weight effects and prior volume effects, collectively called “projection effects” [89, 90]. The Jeffreys prior, by construction, minimizes sensitivity to the choice of parameterization and therefore

⁸<https://github.com/sfschen/velocileptors>

⁹ In [48], it is noted that $\sum m_\nu$ has some degeneracy with H_0 , especially in the CMB lensing likelihood. However, they obtained nearly identical constraints when fixing this parameter compared to enforcing their fiducial prior $\sum m_\nu < 0.26 \text{ eV}$, i.e. the 2σ constraint from the *Planck* primary CMB [3]. While we consider their fiducial prior sufficiently conservative, we note that the authors observed degraded constraints when using a prior several times wider, e.g. from the ground-based KATRIN experiment [87].

Parameter	Prior	Notes
H_0	Unif [20, 100]	[km s ⁻¹ Mpc ⁻¹]
Ω_m	Unif [0.01, 1.0]	
ω_b	$\mathcal{N}(0.02218, 0.00055^2)$	BBN [88]
$\ln(10^{10} A_s)$	Unif [1.61, 3.91]	
n_s	$\mathcal{N}(0.9649, 0.042^2)$	10× <i>Planck</i> [3]
q_{BAO}	Unif [0.9, 1.1]	
$(1 + b_1) \sigma_8$	Unif [0.0, 3.0]	
$b_2 \sigma_8^2, b_s \sigma_8^2$	$\mathcal{N}(0, 5^2)$	
$\alpha_0, \alpha_2, \alpha_4$	$\mathcal{N}(0, 12.5^2)$	+Approx. Jeffreys prior ¹⁰
SN_0	$\mathcal{N}(0, 2^2) \times 1/\bar{n}_g$	+Approx. Jeffreys prior ¹⁰
SN_2	$\mathcal{N}(0, 5^2) \times f_{\text{sat}} \sigma_{1\text{eff}}^2 / \bar{n}_g$	+Approx. Jeffreys prior ¹⁰
SN_4	$\mathcal{N}(0, 5^2) \times f_{\text{sat}} \sigma_{1\text{eff}}^4 / \bar{n}_g$	+Approx. Jeffreys prior ¹⁰

Table 1. Priors used in this work for constraints from the DESI data alone. The physically motivated nuisance parameterization used here is described in detail in [74] and [55]. The prior width of the term SN_0 is multiplied by the Poissonian shot noise $1/\bar{n}_g$, whereas the prior width for the term SN_2 is multiplied by the expected satellite galaxy fraction times the mean satellite velocity dispersion times the Poissonian shot noise, corresponding to the characteristic velocity dispersion [55], and so on for SN_4 .

also minimizes projection effects. In [53] it is shown that for full-shape analysis of the DESI 2024 data, projection effects can become pronounced when opening up the parameter space beyond standard ΛCDM (which we are doing through the addition of the q_{BAO} parameter). Indeed, when analyzing mock DESI data alone without a Jeffreys prior, we observe H_0 offsets at the $\sim 2\sigma$ level; these offsets are corrected almost entirely after enforcing a Jeffreys prior. While the addition of external datasets can help to mitigate biases due to projection effects [53, 86], we conservatively choose to apply the Jeffreys prior to further reduce these effects. We efficiently accomplish this using the technique of [86], who showed that the profile likelihood is a good approximation for a nuisance parameter-marginalized posterior in the presence of a Jeffreys prior. In other words, we simply fix our nuisance parameters (counterterms and stochastic terms) to their best-fit (maximum posterior) values at each point in cosmological+bias parameter space.

4.5 Emulator

A single evaluation of the full EFT theory can take several seconds, which can be prohibitively time-consuming for a single Markov chain Monte Carlo run (MCMC; see [91] and references therein), let alone the many runs needed for testing. We therefore train an emulator to quickly produce approximate theoretical power spectrum multipoles at any given point in cosmological parameter space. We train a 4th-order Taylor series emulator for each tracer, a

¹⁰Jeffreys prior [85] applied in addition to the listed Gaussian prior. In practice, we use an approximation to the Jeffreys prior demonstrated in [86] (see Section 4.4).

functionality that is built into the `desilike` code.¹¹ `desilike` separates the cosmology- and nuisance-dependent parts of the perturbation theory integrals (with the former consuming the bulk of the computation time), so that we only need to Taylor expand in the cosmological parameters.

4.6 Sampling

We run MCMC inference using the `desilike` implementation of the No-U-Turn sampler (NUTS; [92]) on the Perlmutter computing cluster at the National Energy Research Scientific Computing Center (NERSC). We continue sampling until the maximum-eigenvalue Gelman-Rubin statistic [93] satisfies $R - 1 < 0.03$. Because the covered MCMC chains were generated using the emulated EFT theory, after sampling we chose to recover the true posterior distribution via importance sampling. That is, we weight each point in the chain by the ratio of the true posterior probability to emulated posterior probability.¹² We note that after unblinding our analysis, in order to obtain very well-sampled chains for the final combination with several external datasets, we resumed sampling until obtaining an effective sample size (ESS) of 40,000, defined as the total number of MCMC iterations divided by the integrated correlation length of the chains. These are the chains that were used to derive the results presented in this work.

4.7 Validation on Mocks and Unblinding

We chose to perform our analysis “blind” in order to avoid introducing human bias into the results. Rather than blinding via a random transformation of the real data (as was done in [74]), by “blind” we mean that we only tested our analysis settings and pipeline using mocks, before finally deciding to run and view our results using the real data. For our mock testing, we used 25 mock data vectors obtained from AbacusSummit [94, 95] N -body mocks, which are based on halo occupation distribution (HOD) models calibrated to match the clustering of the DESI early data release [72]. The specific mocks we used for testing are described in [96–98]. We used the same covariance matrix described in Section 4.2.

Before running our analysis on real data, we ensured that the following criteria were satisfied. First, we confirmed that among the 25 mock measurements, roughly 68% of our 1σ H_0 constraints captured the fiducial value used in the mocks. The results of this test using mock DESI data alone are shown in Fig. 2, which shows that 18 of the 25 constraints, or 72%, capture the the true H_0 value used in the mocks. Additionally, we observed no significant biases in the parameter constraints when considering two different mock fiber assignment strategies (Fast Fiber Assign [99] and altMTL [100]). As a final check before unblinding our results, we ran our analysis pipeline on the real DESI data, and importance sampled the emulated chains using the true theory as described in Section 4.6. We confirmed (only looking at differences in parameter values) that the mean H_0 values obtained from the emulated and importance-sampled chains differed by less than 0.3σ . After satisfying this final criterion, we unblinded our results and combined with external datasets as described in Section 4.8. We note that our fiducial datasets for this work, i.e. those chosen before unblinding, were: 1) DESI galaxy clustering; 2) *Planck*+ACT CMB lensing; and 3) Ω_m information from each

¹¹<https://desilike.readthedocs.io/en/latest/api/emulators.html#module-desilike.emulators.taylor>

¹²We note that when importance sampling with the true theory, we use the same maximization technique described in Section 4.4 for the counterterms and stochastic terms. That is, at a given point in cosmological+bias parameter space, we use the best-fit counterterms and stochastic terms according to the true posterior.

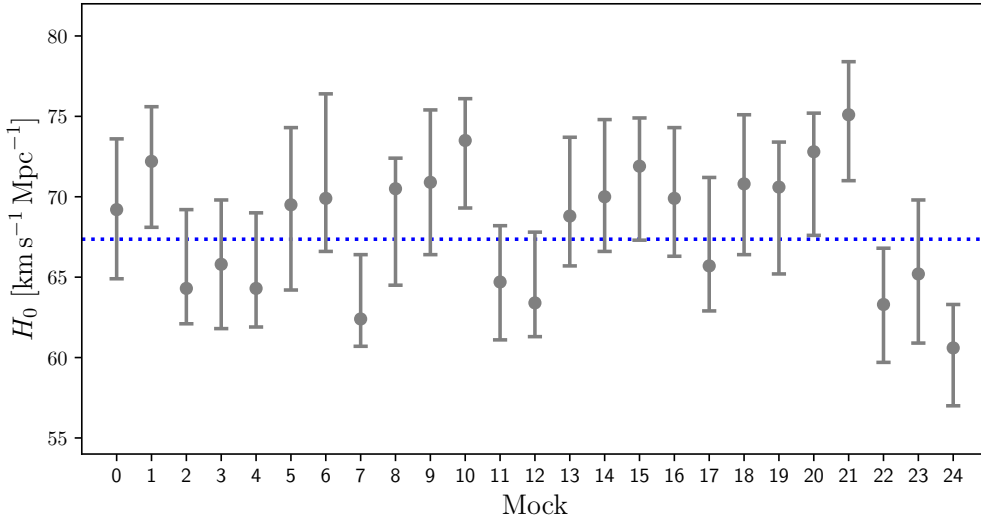


Figure 2. 68% credible-interval constraints on the parameter H_0 , for all 25 AbacusSummit mocks used for the testing of our analysis pipeline. The blue dotted line shows the true underlying H_0 value of the mocks. 18 of the 25 credible intervals (72%) capture the true H_0 value.

of the DESY5/Pantheon+/Union3 SN-Ia datasets. After unblinding, we decided to further combine our result with Ω_m information from the DESI Ly α forest as described in Section 2. Both sets of results are presented in Section 5. Additionally, we note that our initial run on real data did not include the clustering of the BGS sample; however, this negligibly affected our main results.

4.8 Combination with External Datasets

In this paper we combine the base DESI clustering-only analysis with external data at the likelihood level by reweighting our MCMC chains. In the case of CMB lensing, we perform importance sampling using the *Planck*+ACT likelihood described in Section 3. We note that the combination with CMB lensing at the likelihood level is permissible because the covariance between the projected statistics and the multipoles is negligible [101]. Meanwhile for DESY5 and Pantheon+, we note that the constraints on Ω_m are Gaussian, leading to a simple analytic re-weighting. However, we find that the Union3 and Ly α constraint on Ω_m is not Gaussian, so in these cases we use `CombineHarvesterFlow`¹³ [102] to find the joint constraints.

5 Results

The results of this work are summarized in Table 2. In Fig. 3 we present our constraints on the parameters $\{H_0, \Omega_m, \ln(10^{10} A_s), n_s, q_{\text{BAO}}\}$ using the DESI galaxy clustering data alone (BGS + LRGs + ELGs + QSOS), as well as when combining with *Planck*+ACT CMB lensing and Ω_m information from the DESI Ly α forest ($\Omega_m^{\text{Ly}\alpha\text{AP}}$). We first note the high quality of the constraints afforded by the DESI data alone, especially considering that we have

¹³<https://github.com/pltaylor16/CombineHarvesterFlow>

Dataset(s)	H_0 [km s ⁻¹ Mpc ⁻¹]
DESI galaxy clustering only	71.2 ± 4.1
DESI + CMB lensing	70.1 ^{+2.7} _{-3.3}
DESI + CMB lensing + $\Omega_m^{\text{Ly}\alpha\text{AP}}$	69.6 ^{+2.4} _{-2.6}
DESI + CMB lensing + Ω_m^{DESY5} (+ $\Omega_m^{\text{Ly}\alpha\text{AP}}$)	66.1 ^{+1.8} _{-2.0} (66.7 ^{+1.7} _{-1.9})
DESI + CMB lensing + $\Omega_m^{\text{Pantheon+}}$ (+ $\Omega_m^{\text{Ly}\alpha\text{AP}}$)	67.6 ^{+1.9} _{-2.2} (67.9 ^{+1.9} _{-2.1})
DESI + CMB lensing + Ω_m^{Union3} (+ $\Omega_m^{\text{Ly}\alpha\text{AP}}$)	67.3 ^{+2.1} _{-2.4} (67.8 ^{+2.0} _{-2.2})

Table 2. H_0 constraints obtained in this work. Limits shown are 68% credible intervals.

only analyzed data from the first DESI data release, which corresponds to the first of five total years of observations. In particular, the DESI clustering-only sound horizon-marginalized H_0 constraint, $71.2 \pm 4.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$, is already more precise than the analogous constraints obtained from BOSS DR12 in [47] and [48]. As discussed in Section 2, the six DESI tracers, while individually carrying k_{eq} -characteristic degeneracies in the $\Omega_m - H_0$ plane, each intersect to create a more precise joint constraint. The addition of CMB lensing primarily helps to improve the H_0 constraint by intersecting the DESI contour at a slightly steeper angle in the $\Omega_m - H_0$ plane. To a lesser extent, CMB lensing additionally improves the H_0 measurement by better constraining the amplitude A_s of the primordial power spectrum, which also displays some degeneracy with the Hubble constant. With the addition of Ω_m information from the DESI Ly α forest, we obtain our tightest constraints independent of supernovae (DESI clustering + CMB lensing + $\Omega_m^{\text{Ly}\alpha\text{AP}}$): $H_0 = 69.6^{+2.4}_{-2.6} \text{ km s}^{-1} \text{ Mpc}^{-1}$. We finally note that even when allowing the sound horizon rescaling parameter q_{BAO} to vary freely with an uninformative prior, our data broadly seem to prefer values near the Λ CDM prediction of $q_{\text{BAO}} = 1.0$. This is also the case when combining with CMB lensing and $\Omega_m^{\text{Ly}\alpha\text{AP}}$; the full combination of these datasets gives the constraint $q_{\text{BAO}} = 0.995^{+0.021}_{-0.022}$.

In Fig. 4 we show our full constraints on H_0 , Ω_m , and q_{BAO} using all datasets listed in Section 3. On the left we show the three dataset combinations that were chosen before unblinding: DESI galaxy clustering + CMB lensing + $\Omega_m^{\text{DESY5}}/\Omega_m^{\text{Pantheon+}}/\Omega_m^{\text{Union3}}$. On the right we show our tightest constraints, in which we additionally include Ω_m information from DESI Ly α , again noting that this was decided after unblinding (as discussed in Section 4.7). Our tightest H_0 constraints obtained in this work are:

$$H_0 = \begin{cases} 66.7^{+1.7}_{-1.9} \text{ km s}^{-1} \text{ Mpc}^{-1} & (\text{DESI} + \text{CMB lensing} + \Omega_m^{\text{Ly}\alpha\text{AP}} + \Omega_m^{\text{DESY5}}) \\ 67.9^{+1.9}_{-2.1} \text{ km s}^{-1} \text{ Mpc}^{-1} & (\text{DESI} + \text{CMB lensing} + \Omega_m^{\text{Ly}\alpha\text{AP}} + \Omega_m^{\text{Pantheon+}}) \\ 67.8^{+2.0}_{-2.2} \text{ km s}^{-1} \text{ Mpc}^{-1} & (\text{DESI} + \text{CMB lensing} + \Omega_m^{\text{Ly}\alpha\text{AP}} + \Omega_m^{\text{Union3}}) \end{cases}$$

This translates to a $\sim 2.9\%$ average constraint, which as far as the authors are aware is the most precise sound horizon-free H_0 measurement to date using a Full Modeling approach.¹⁴ We can interpret our combined constraints on the parameter q_{BAO} as a test of whether

¹⁴We note that [25] obtained a similarly precise constraint using ShapeFit and data from BOSS DR12; their template-based approach and other differences in their analysis pipeline (in particular their inclusion of “uncalibrated, unnormalized” BAO information, which we plan to investigate in future work) make a direct comparison difficult.

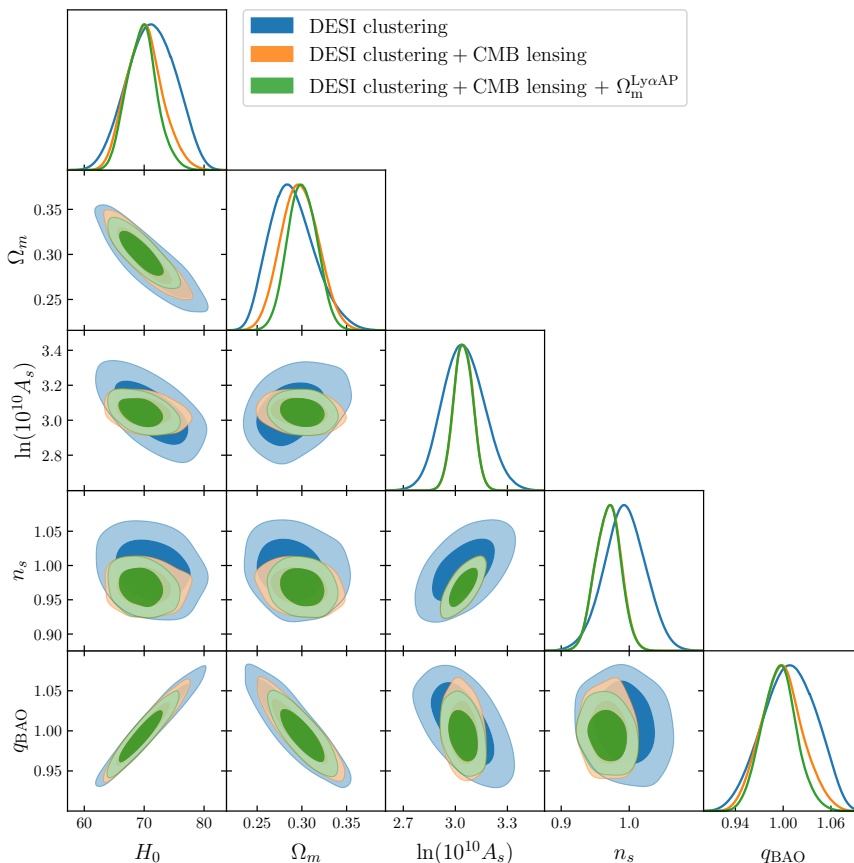


Figure 3. Cosmological parameter constraints from: 1) DESI galaxy clustering only (BGS + LRG + ELG + QSO); 2) DESI clustering + CMB lensing; and 3) DESI clustering + CMB lensing + $\Omega_m^{\text{Ly}\alpha\text{AP}}$. CMB lensing refers to the *Planck*+ACT lensing-only likelihood described in Section 3. We note that Ly α was added after unblinding, as discussed in Section 4.7.

the full dataset is consistent with Λ CDM, in the context of sound horizon-modifying new physics. Because our marginalized posteriors are asymmetric, we adopt the non-Gaussian tension estimation technique of [103]. We find that our full joint constraints are consistent with Λ CDM ($q_{\text{BAO}} = 1.0$) at up to 1.8σ when including Ly α , or 2.0σ without Ly α . We note that we observe a slight preference for $q_{\text{BAO}} < 1.0$, which is driven by the lower Ω_m preferred by DESI relative to the SN Ia datasets. Future DESI data releases will help to determine whether or not this is simply a statistical fluctuation.

6 Discussion

In Fig. 5 we show how the measurements from this work fit into the current landscape of H_0 measurements. We note two interesting observations. First is that even without using information from the sound horizon scale, our tightest H_0 measurements are still in 2.9σ , 2.3σ , or 2.2σ tension with SH0ES, when combining with DESY5, Pantheon+, and Union3 respectively (again, using the non-Gaussian tension estimation technique of [103]). Without including Ly α (our fiducial data choice made before unblinding), these tensions are 3.0σ , 2.3σ ,

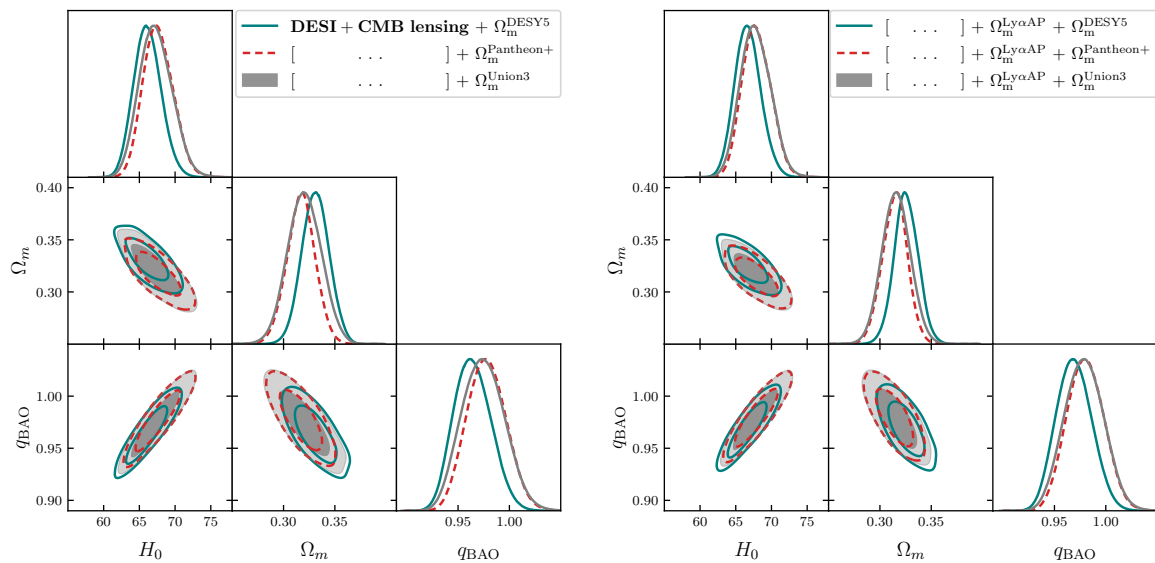


Figure 4. Constraints obtained in this work on the parameters H_0 , Ω_m , and q_{BAO} . **Left:** Constraints from DESI galaxy clustering + CMB lensing + Ω_m information from each of the DESY5, Pantheon+, and Union3 supernova datasets. **Right:** Same as left, with the addition of Ω_m information from the DESI Ly α forest, as described in Section 2. We note that Ly α was added after unblinding. CMB lensing refers to the *Planck*+ACT lensing-only likelihood described in Section 3.

and 2.3σ . Second, our measurement is consistent with other early-time measurements that fully or mostly rely on the sound horizon scale. This would indicate that our measurement is consistent with Λ CDM, and in particular we do not find evidence for new early-Universe physics. We do note, however, that in Section 5 we found that the dataset combination (DESI clustering + CMB lensing + Ω_m^{DESY5}) reaches a 2.0σ deviation from the Λ CDM prediction of $q_{\text{BAO}} = 1.0$, and it will be interesting to see how this changes with the coming three-year and five-year data releases of DESI.

In [47], the authors performed a similar analysis for a simulated Euclid-like survey in an early dark energy (EDE) universe. Two EDE models were considered; the best-fit EDE model from *Planck* + SH0ES data ([105]; weaker EDE), and the EDE model favored by ACT ([106]; stronger EDE). They then measured H_0 both with and without sound horizon information (assuming a Λ CDM fiducial cosmology), finding that EDE generally shifts the sound horizon H_0 measurement toward higher values relative to the sound horizon-free measurement, which is expected due to the reduction of the physical sound horizon scale. The consistency we observe in this work between various early-time H_0 measurements, regardless of whether they rely on the sound horizon scale or are independent of it, begins to put pressure on more extreme beyond- Λ CDM models such as ACT-favored EDE. However, we cannot rule out less extreme models of new physics (such as *Planck* EDE). The volume probed by galaxy surveys will increase rapidly in the coming years; as more data is collected and the precision of sound horizon-free H_0 measurements improves, even stronger constraints will be placed on such models of new early-Universe physics.

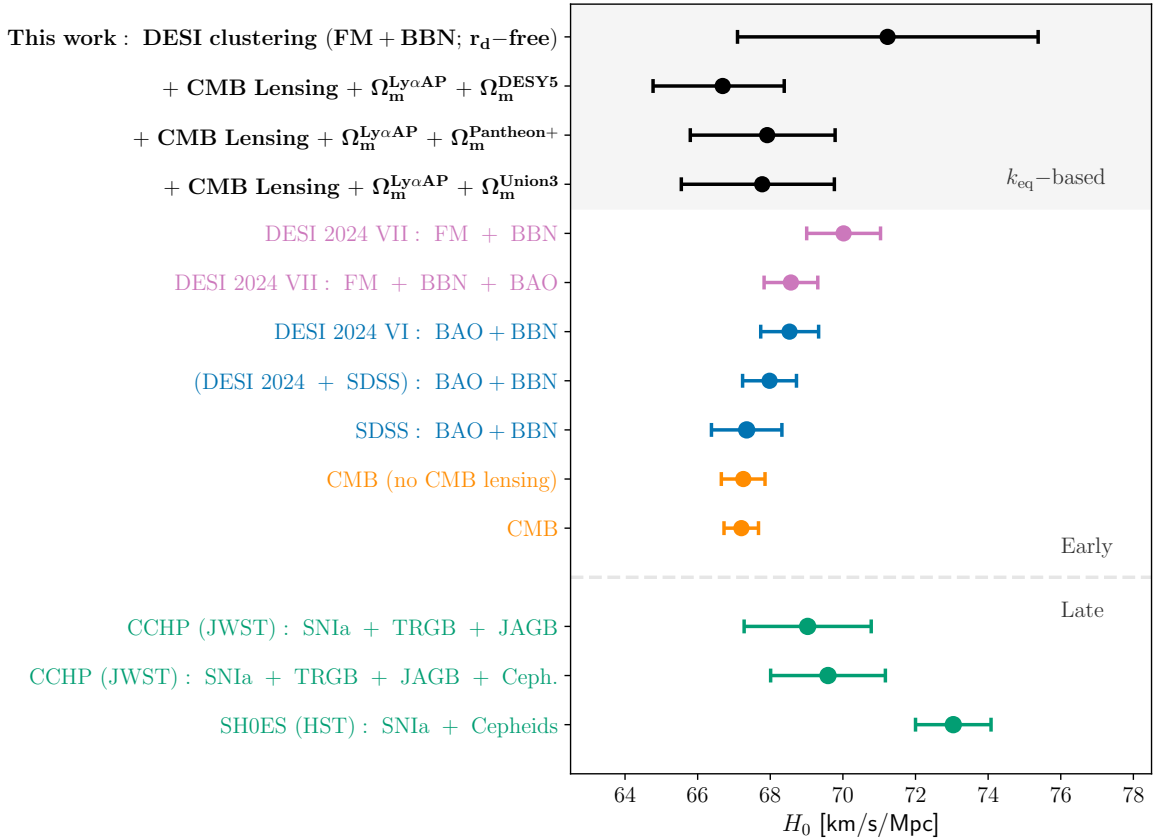


Figure 5. 68% credible interval constraints from various measurements of the Hubble constant. The black whiskers with bolded labels show constraints obtained in this work. We show our H_0 measurement from DESI galaxy clustering alone (BGS + LRG + ELG + QSO), as well as when combined with *Planck*+ACT CMB lensing and Ω_m information from the DESI Ly α forest and each supernova dataset as discussed in Section 5. The pink whiskers show constraints from the DESI 2024 full-shape analysis [53], while the blue whiskers show constraints from the DESI 2024 [11] and/or the Sloan Digital Sky Survey (SDSS; [104]) BAO analyses. CMB H_0 measurements from the combination of *Planck* and ACT data are shown in orange. Finally, the green whiskers at the bottom show local distance ladder H_0 constraints from the Chicago-Carnegie Hubble Program (CCHP; [60]) and SH0ES [2] teams. As indicated, the CCHP measurements used data from the James Webb Space Telescope (JWST), whereas the SH0ES measurement used the Hubble Space Telescope (HST). TRGB stands for the Tip of the Red Giant Branch calibration method, and JAGB stands for the J-region Asymptotic Giant Branch method (see the relevant references for further information).

7 Conclusions

In light of the Hubble tension, there is significant interest in measuring the Hubble constant H_0 using independent techniques. We have performed a precise measurement of H_0 without relying on information from the sound horizon scale, using data from the first data release of the DESI survey. In Section 2 we demonstrated our methodology for removing the sound horizon information from our measurement, rescaling and marginalizing over the sound horizon distance using the technique developed in [47]. By jointly analyzing the full-shape clustering of DESI LRGs, ELGs, quasars, and the bright galaxy sample in six redshift bins, we have obtained constraints that already surpass those from the completed BOSS

survey (e.g. [47] and [48]). When further combining with CMB lensing, uncalibrated type Ia supernovae, and Alcock-Paczyński information from the DESI Ly α forest, we have obtained a sub-3% constraint on H_0 , the most precise sound horizon-free measurement from LSS to date using a Full Modeling approach.

The complete results from this work were shown in Section 5. Using the full joint dataset including DESI clustering + CMB lensing + $\Omega_m^{\text{SN Ia}} + \Omega_m^{\text{Ly}\alpha\text{AP}}$, our tightest H_0 constraints are $66.7^{+1.7}_{-1.9}$, $67.9^{+1.9}_{-2.1}$, and $67.8^{+2.0}_{-2.2}$ km s $^{-1}$ Mpc $^{-1}$, when combining with DESY5, Pantheon+, and Union3, respectively. We highlighted two interesting observations. The first is that even without including information from the sound horizon scale, our constraints are still in 2.2-3.0 σ tension with the H_0 measurement from the SH0ES collaboration [2]. Second, we observed that our measurement is broadly consistent with other early-time H_0 measurements that *do* rely on the sound horizon scale. As discussed in Section 6, some early-Universe solutions to the Hubble tension (e.g. early dark energy) may lead to deviations in sound horizon-dependent measurements of H_0 , compared to those that are independent of the sound horizon scale. Therefore, we have found no significant evidence of new early-Universe physics in this work. Future data releases from DESI and other ongoing/upcoming galaxy surveys, however, will allow increasingly precise constraints on such models. It will be exciting to see how this data changes our understanding of the Hubble tension.

8 Data Availability

The data used in this analysis will be made public along the Data Release 1 (details in <https://data.desi.lbl.gov/doc/releases/>).

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