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Dark Energy Spectroscopic Instrument (DESI) survey Year 1 results

DESI2024: Dark Energy Spectroscopic Instrument (DESI) survey, presentation of Year 1 results

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

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Abstract: The series of papers included in this special issue represent the first cosmological measurements from the Dark Energy Spectroscopic Instrument (DESI). These papers present the validation of the DESI clustering catalogs, the methodology for the cosmology measurements, and the full cosmology implications. These measurements were derived from a catalog of approximately 6.4 million extragalactic sources in a redshift range of $0.1 < z < 4.2$. Owing to advances in fiber positioner technology and to a larger telescope, this sample was acquired in only one year of observation, yet is more than double the size of the galaxy and quasar samples from the first four phases of the Sloan Digital Sky Survey (SDSS) that spanned 20 years. With these new galaxy and quasar catalogs, the DESI collaboration completed percent-level constraints on the cosmic expansion history and the growth of structure. In turn, these new measurements provided a new platform from which to test the equation of state of dark energy, the summed mass of the three neutrino mass eigenstates, global curvature, and General Relativity. By surpassing the precision of the previous generation spectroscopic survey, the results in this special issue mark the transition in the field of cosmology to Stage-IV dark energy science.

Keywords: baryon acoustic oscillations, cosmological parameters from LSS, redshift surveys

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1 Introduction

The Dark Energy Spectroscopic Instrument (DESI)[1] was conceived in 2009, roughly the same time that the Stage-III Baryon Oscillation Spectroscopic Survey (BOSS)[2] was beginning its observational program. Designed as a Stage-IV dark energy experiment, the spectroscopic samples produced by DESI will lead to an order of magnitude improvement in our understanding of dark energy, as quantified by the area of the posterior on a two-parameter model that allows for time-evolution of the equation of state (see e.g., [1]).

Spectroscopic samples for DESI are generated from imaging data in the g-, r- and z-band filters acquired from the Bok 2.3m telescope, the Blanco 4m telescope, and the Mayall 4m telescope. The selection of targets was aided by additional data from the WISE (Wide Infrared Survey Explorer) and Gaia space telescopes[3] [2]. With the goal of measuring baryon acoustic oscillations (BAO) and the growth of structure through redshift-space distortions (RSD), the spectroscopic targets fall into four distinct classes, chosen for the possibility to achieve reliable redshifts at high efficiency. Bright galaxies are selected to a limiting observed magnitude to span the range $0 < z < 0.4$, luminous red galaxies are selected by colors expected from a passively evolving population over $0.4 < z < 1.1$, and bright [O II] emission-line galaxies are targeted up to $z = 1.6$. Quasars are targeted as direct tracers to $z < 2.1$, and at higher redshifts, are selected to provide a backlight for Lyman-alpha forest absorption. Over a 14,000 square degree footprint, DESI is expected to produce a spectroscopic sample of nearly 40 million extragalactic objects. The potential remains to expand the sample size and footprint even further.

DESI is mounted on the Nicholas U. Mayall Telescope at Kitt Peak National Observatory in Arizona. The collaboration is honored to be permitted to conduct scientific research on Iolkam Du'ag (Kitt Peak), a mountain with particular significance to the Tohono O'odham Nation.

The instrument consists of a 5000-fiber robotic positioner system mounted at the prime focus of the 4-meter telescope. The 47.5-meter fibers complete their run inside a humidity- and temperature-controlled room that houses ten spectrographs, each capable of resolving the spectral features of galaxies and quasars over wavelengths ranging from 360 nm to 980 nm [3]. Commissioning of the instrument finished on March 21, 2020, just as the Covid-19 pandemic

[1] https://www.desi.lbl.gov/.
[2] https://www.sdss3.org/surveys/boss.php.
[3] See https://www.legacysurvey.org/.

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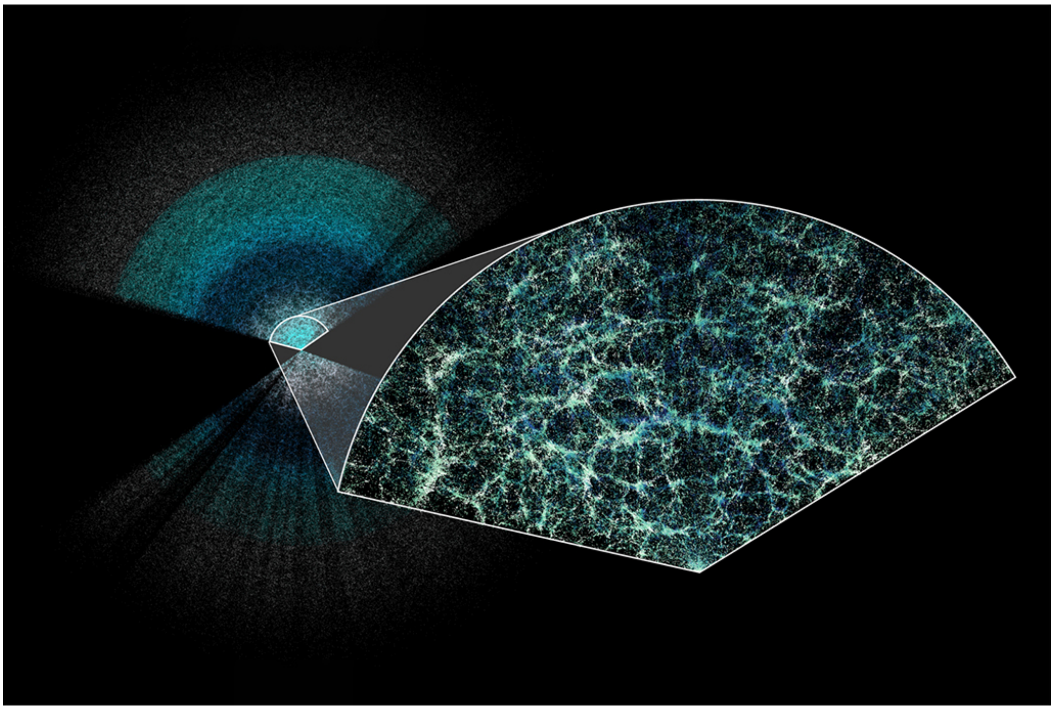

Figure 1. DESI has made the largest 3D map of our universe to date. Earth is at the center of this thin slice of the full map. In the magnified section, it is easy to see the underlying structure of matter in our universe. (Credit: Claire Lamman/DESI collaboration; custom colormap package by cmastro). Reproduced with permission from Claire Lamman/DESI collaboration.

was rearing its ugly head. DESI returned to operations in December 2020 and began its full survey on May 14, 2021. The final observation for the first year data sample occurred on June 14, 2022, when the Kitt Peak Observatory was evacuated due to the 30,000-acre Contreras forest fire. Although the fire swept over the peak of the observatory, neither DESI nor the Mayall Telescope suffered any meaningful damage thanks to the effort of roughly 100 firefighters deployed to the summit. Observations for the next data sample resumed several months later and continue to this day.

2 Year 1 results

The DESI collaboration used the Year 1 spectroscopic sample to demonstrate the robustness, precision, and accuracy that is possible in measuring cosmological features in large-scale structure. These robustness tests included a full assessment of the imaging and spectroscopic data quality, of the variations of the cosmology results with the methodology or hypotheses on the underlying cosmology, and of the stability of the conclusions with respect to various data splits.

While informed by previous work, the results in this special issue represent a major advance over the previous studies from the SDSS collaboration. Not only is DESI using the largest data set both in terms of numbers and volume (see figure 1), but the analysis is benefiting from major improvements. Namely, the study was blinded at the catalog level to mitigate confirmation bias. The collaboration used a unified framework and a set of systematic tests across all sources over the full redshift range. The BAO results include a new

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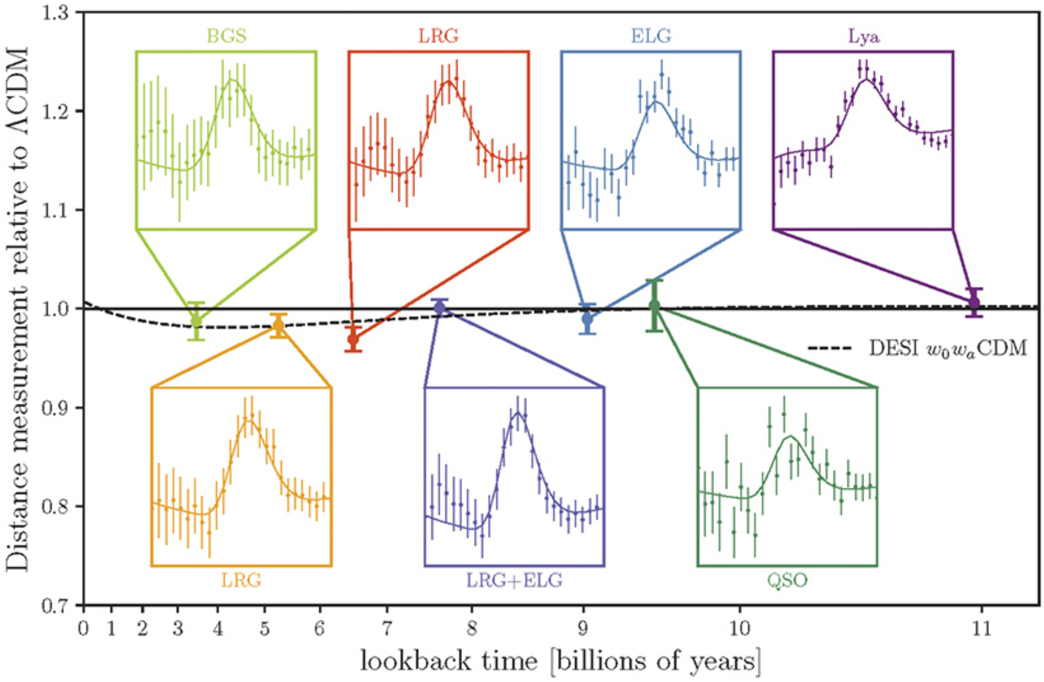

Figure 2. DESI's Hubble diagram plots a characteristic pattern — baryon acoustic oscillations, or BAO "bubbles" — at different ages of the universe. The amount of dark energy determines how fast the universe grows, and therefore the size of the bubbles. The solid line is how big ΛCDM predicts the bubbles will be, while the dashed line shows the prediction from a different model where dark energy evolves with time. DESI will gather more data to determine which model is a better description of the universe. Reproduced with permission from Arnaud de Mattia/DESI collaboration.

assessment of the underlying theory while the growth results include a thorough evaluation of the parameterization, priors, and scale cuts across several models based on effective field theory. The imaging data is significantly deeper than what was used for the selection of targets in SDSS, and the effects of varying quality in the imaging data have been re-evaluated with a new perspective. The Lyman-alpha forest measurements were performed at a higher signal-to-noise than in previous studies, with deeper observations planned in the coming years.

The final result of the studies found in this special issue is a series of BAO measurements at higher aggregate precision than in all previous surveys. Figure 2 shows DESI's Hubble diagram extracted from the BAO measurements. The systematic errors resulting from theory, the varying populations of galaxies within halos, and the assumptions of the underlying cosmological model are each an order of magnitude smaller than the statistical uncertainties. The sum of these effects leads at most to a 5% decrease in the constraining power of the BAO measurements from galaxies and quasars. Meanwhile, studies on mock catalogs and with varying data splits revealed no sources of systematic error in the Lyman-alpha forest BAO measurement that were quantifiable given the statistical precision of the Year 1 data sample. The results from this first year study, when combined with those from Cosmic Microwave Background (CMB) experiments and various samples of Type Ia supernovae, show a preference for a time-varying dark energy. The Year 1 sample also sheds new light on the tensions that have appeared, depending on the approach or combination of cosmological

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probes utilized, on the measurements of today's expansion rate (the H_0 parameter) and of the amplitude of matter density fluctuations. The results presented in this special issue show a good agreement with the value of H_0 derived from CMB data alone under the assumption of a ΛCDM model. Based on DESI data alone there is no indication for deviations from ΛCDM, from general relativity nor indication of other non-standard physics that would ease currently-known cosmological tensions.

3 Conclusions and outlook

These results from the Year 1 sample are the first step in a sequence of increasingly important and diverse results from the DESI collaboration. Science analyses within the DESI collaboration are organized thematically across eight working groups. Comprehensive results representing the consensus of the DESI collaboration are planned through Key Projects, studies that are associated with specific data samples are coordinated within the working groups. The papers in this issue authored by "DESI Collaboration, et al." are the synthesized results of five different Key Projects from the first-year sample. These are referred to as "Key Papers". Other papers are referred to as "supporting papers". All authors, whether of these Key Papers or the supporting papers, have made significant contributions to the work presented or are DESI builders, a status that recognizes at least the equivalent of 1.5 years of contribution to DESI infrastructure. Key Papers have alphabetical author lists, while all other DESI papers have a 2-tier author list, where the first tier is limited to the top contributors of that specific analysis. In anticipation of the Year 3 data sample, the working groups have identified eight new Key Projects.

The Year 3 sample is now complete and the work toward those new Key Projects has begun. The updated catalogs include 31 million galaxies and quasars and 11 million stars. The enhanced goals for the Year 3 Key Projects include:

- Accelerated BAO analysis following the Year 1 methodology;
- Improved precision on Year 1 measurements through use of higher-order statistics in the clustering of galaxies and quasars and models that rely on information beyond the BAO scales in the Lyman-alpha forest;
- Enhanced measurements of structure growth by using cross-correlations with CMB lensing, cross-correlations with galaxy lensing, and peculiar velocities inferred from low redshift measurements of the Tully-Fisher relation, fundamental plane, and Type Ia supernovae; and
- Measurements of the mass profile of the Milky Way using six-dimensional phase space data from DESI and Gaia.

Relative to the combined SDSS and Planck results, the final DESI BAO and Planck CMB samples are expected to lead to a factor 4.5 improvement in constraining a dark energy equation of state that varies with time. An even larger improvement is expected when combining those results with the enhanced measurements of these year-3 Key Projects, and eventually, when using those techniques in the final DESI samples. Using only DESI BAO

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and the same CMB results as in the year 1 analysis, an extended DESI program running through the end of 2028 is expected to achieve a discriminating power ranging from 3.5 to 4.9 sigma between a ΛCDM cosmology and any of the time-varying dark-energy models preferred by combination of BAO, CMB, and Type Ia supernova reported in the year-1 DESI results found in this issue.

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