

Astro2020 APC White Paper

The Dark Energy Spectroscopic Instrument (DESI)

Thematic Areas:

- Planetary Systems
- Star and Planet Formation
- Formation and Evolution of Compact Objects
- Cosmology and Fundamental Physics
- Stars and Stellar Evolution
- Resolved Stellar Populations and their Environments
- Galaxy Evolution
- Multi-Messenger Astronomy and Astrophysics

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Abstract: We present the status of the Dark Energy Spectroscopic Instrument (DESI) and its plans and opportunities for the coming decade. DESI construction and its initial five years of operations are an approved experiment of the U.S. Department of Energy and is summarized here as context for the Astro2020 panel. Beyond 2025, DESI will require new funding to continue operations. We expect that DESI will remain one of the world's best facilities for wide-field spectroscopy throughout the decade. More about the DESI instrument and survey can be found at <https://www.desi.lbl.gov>.

1 An Overview of DESI: 2020-2025

DESI is an ambitious multi-fiber optical spectrograph sited on the Kitt Peak National Observatory Mayall 4m telescope, funded to conduct a Stage IV spectroscopic dark energy experiment. DESI features 5000 robotically positioned fibers in an 8 deg^2 focal plane, feeding a bank of 10 triple-arm spectrographs that measure the full bandpass from 360 nm to 980 nm at spectral resolution of 2000 in the UV and over 4000 in the red and IR (Martini et al. 2018). DESI is designed for efficient operations and exceptionally high throughput, anticipated to peak at over 50% from the top of the atmosphere to detected photons, not counting obscuration of the telescope or aperture loss from the 1.5" diameter fibers. More information is in Table 1.

As of this writing in July 2019, DESI construction is nearly complete and the instrument is being installed at the Mayall telescope. The new prime-focus corrector was operated on sky in April/May 2019 and confirmed to produce sharp images. All ten petals of the robotic positioners and all fibers have been constructed; these are being installed on the telescope in July (Figure 1). Six of the ten spectrographs are installed and entering off-sky commissioning (Figure 2 and 3); the other four should arrive in fall 2019. We anticipate spectroscopic first-light in October 2019, with commissioning running through January 2020. The collaboration will then operate a 4-month Survey Validation program in spring 2020 and begin the 5-year survey in summer 2020.

Key Science Goals: The DESI Collaboration will use this facility to conduct a 5-year survey of galaxies and quasars, covering $14,000 \text{ deg}^2$ and yielding 34 million redshifts. The mission-need science of this survey is the study of dark energy through the measurement of the cosmic distance scale with the baryon acoustic peak method as a standard ruler and through the study of the growth of structure with redshift-space distortions. The survey will further allow measurement of other cosmological quantities, such as neutrino mass and primordial non-Gaussianity, as well as studies of galaxies, quasars, and stars.

The DESI survey uses a sequence of target classes to map the large-scale structure of the Universe from redshift 0 to 3.5 (Aghamousa et al. 2016). In dark and grey time, DESI will utilize quasars, emission-line galaxies, and luminous red galaxies. Over 4M luminous red galaxy sample will cover $0.3 < z < 1$, including coverage to $z \sim 0.8$ at a density twice that of SDSS-III BOSS. The emission-line galaxy sample is the largest set, 18M, covering $0.6 < z < 1.6$ and providing the majority of the distance scale precision. 2.4M quasars selected from their WISE excess will extend the map. Importantly, these will yield Lyman α forest measurements along 600K lines-of-sight, from which we will measure the acoustic oscillations at $z > 2$.

In bright time, DESI will conduct a flux-limited survey of 10M galaxies to $r \approx 19.5$, with a median redshift around 0.2. This will allow dense sampling of a volume over 10 times that of the SDSS MAIN and 2dF GRS surveys, which we expect will spur development of cosmological probes of the non-linear regime of structure formation.

In addition to extragalactic targets, DESI will observe many millions of stars. About 10M stars at $16 < G < 19$ will fill unused fibers in the bright time program, and we will conduct a backup

Nicholas U. Mayall Telescope	
Location	Kitt Peak National Observatory, Tohono O'odham Nation, Arizona
Coordinates	31°57'48"N, 111°36'00"W
Elevation	2,120 m
Primary mirror	3.8m diameter, f/2.8, 1.8m central DESI obscuration
Dark Energy Spectroscopic Instrument (DESI)	
Number of fibers	5,000
Field of view	8.0 deg ² (corrected), 7.5 deg ² (populated)
Corrector design	4 lenses + 2 ADC elements
Corrected focal ratio	3.68 (on-axis), 3.86 (average over FOV)
Fiber density on-sky	667 / deg ²
Focal-plane scale	67.5 μm/arcsec (on axis); 70.8 μm/arcsec (average over FOV)
Fiber core diameter	107 μm
Fiber pitch	10.4 mm, hexagonal close pack in 10 focal-plane wedges ("petals")
Fiber patrol region	Circular, 12 mm diameter
Repositioning time	< 45 s
Positioning accuracy	2 μm RMS
Guiding	10 guide-focus-alignment cameras, 1 per petal, 29 arcmin ² each
Spectrographs	10 x 3-arm spectrographs, 500 fibers each
Wavelength range	360–980 nm
Spectral resolution	360–593 nm (Blue Channel): 2,000–3,200 566–772 nm (Red Channel): 3,200–4,100 747–980 nm (NIR Channel): 4,100–5,100
Detectors	30 CCDs, 4,096 x 4,096 pixels, 15 μm pitch
Read + dark noise	< 4 electrons
End-to-end throughput	43.0% @ 450nm, 45.4% @ 650nm, 50.5% @ 850nm (estimated, telescope x fiber system x spectrographs x detectors)
DESI Surveys	
Survey area	14,000 deg ² fully covered by 2,000 pointings ("tiles")
Survey duration	5 years: CY2020–CY2025
Survey strategy	Key Project (dark time): 10,000 tiles in 5 layers of 2,000 tiles each Bright Time Survey: 6,000 in 3 layers of 2,000 tiles each
Survey samples (baseline)	4.0 million Luminous Red Galaxies, $z = 0.4 - 1.0$ (dark time) 17.1 million Emission Line Galaxies, $z = 0.6 - 1.6$ (dark time) 1.7 million tracer QSOs, $z < 2.1$ (dark time) 0.7 million Ly- α QSOs, $z > 2.1$ (dark time) 9.8 million bright galaxies, $z = 0.05 - 0.4$ (bright time) 10 million Milky Way stars (bright time)

Table 1: DESI at a glance.

program of brighter stars when observing conditions (clouds, moon, and/or seeing) prevent useful data from being collected on extragalactic targets. Because DESI is a bench-mounted spectrograph with sub-degree temperature stability, we anticipate velocity precision to ~ 1 km/s.

The DESI Collaboration plans for release of annual data sets, including survey selection functions and mock catalogs suitable for clustering analyses, following completion of its cosmology key projects.

Target Selection: In preparation of target selection for DESI, the Collaboration has played a leading role in the execution of the Legacy Survey imaging program, using nearly 1000 nights on the Blanco, Mayall, and Bok telescopes to image $15,000 \text{ deg}^2$ to $g = 24$, $r = 23.4$, and $z = 22.5$ depth, co-reduced with 5 years of WISE satellite imaging (Dey et al. 2019). This is the deepest coverage of the full high-latitude sky in the Northern hemisphere (Figure 4). The imaging data and catalogs have had 8 data releases, available at <http://legacysurvey.org>, the last of which reaches over $19,000 \text{ deg}^2$ by inclusion of the 5-year Dark Energy Survey. Hence, DESI has already provided an extensive data product for the general astronomical community.

As regards this first five-year survey with DESI, we stress the opportunity of this U.S.-led project

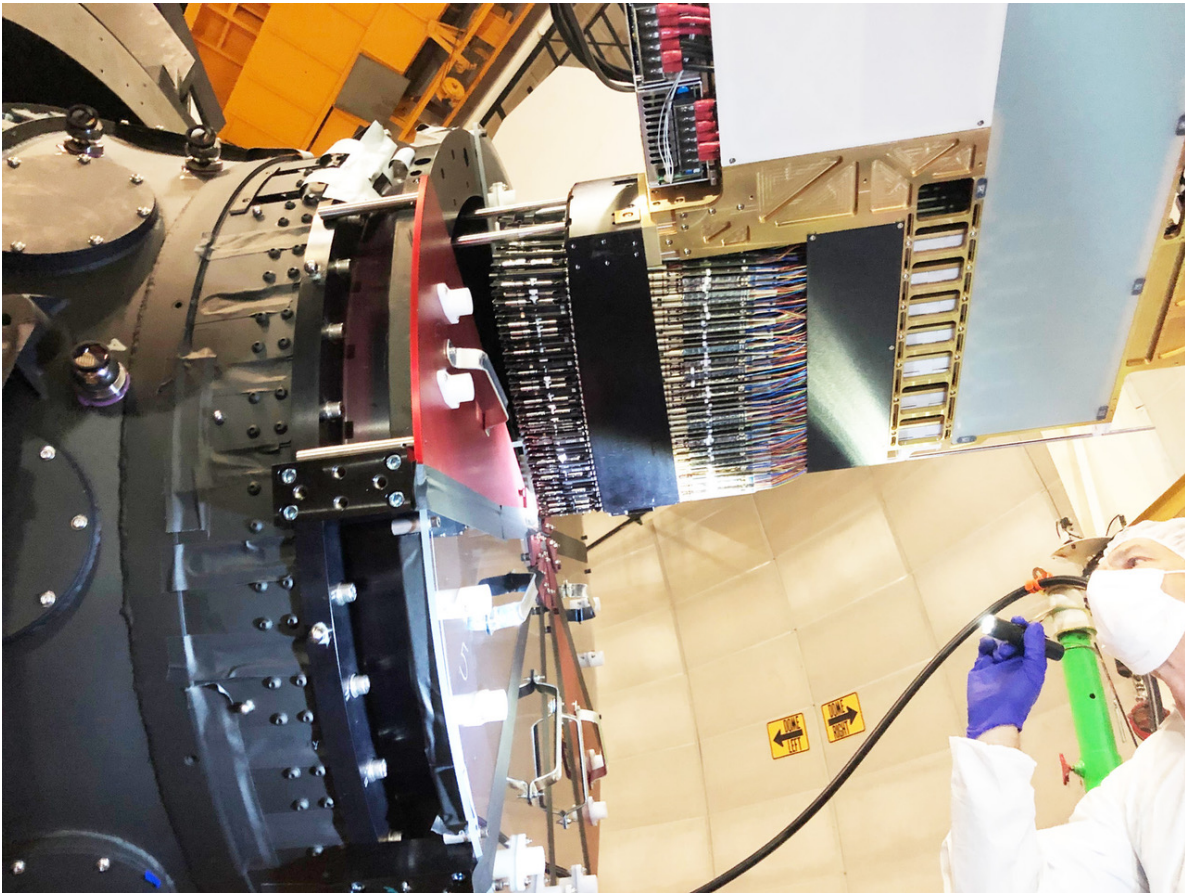


Figure 1: The first of 10 focal plate petals installed at the Mayall prime focus (June 26, 2019).

to conduct cutting-edge dark energy research, both in its own right and in coordination with optical, millimeter, and X-ray imaging data sets. As well illustrated by the SDSS, the combination of spectroscopy and imaging unlocks a wide range of applications.

Organization: DESI is being built by the DESI Collaboration with primary funding from the U.S. Department of Energy, and additional funding from the National Science Foundation, the Science and Technologies Facilities Council of the United Kingdom, the Gordon and Betty Moore Foundation, the Heising-Simons Foundation, the National Council of Science and Technology of Mexico, the French Alternative Energies and Atomic Energy Commission (CEA), and by the DESI Member Institutions. The DESI Collaboration currently has more than 600 total members from 79 institutions from 13 countries around the world. Of those, ~ 200 are senior members, and ~ 400 are early career scientists.

With DESI, the Mayall telescope is dedicated to this single instrument configuration (unlike DECam on the Blanco, which could also mount a secondary mirror). The DOE Office of Science High-Energy Physics division will be the primary funder of the DESI survey, including the operation of the Mayall telescope through the 5-year survey. The survey will utilize at least the darkest 21 nights per lunation, plus engineering time, and potentially may use all of the telescope



Figure 2: Six of the ten 3-armed DESI spectrographs, installed in their thermal enclosure.

time.

Cost: The DESI construction project has cost \$75M, with \$56M from the DOE and the balance by other partners and institutional buy-ins. Survey operations are budgeted at \sim \$12M/year, split approximately one-third site operations, and the rest supporting the instrument, the survey planning, and data processing and catalog creation.

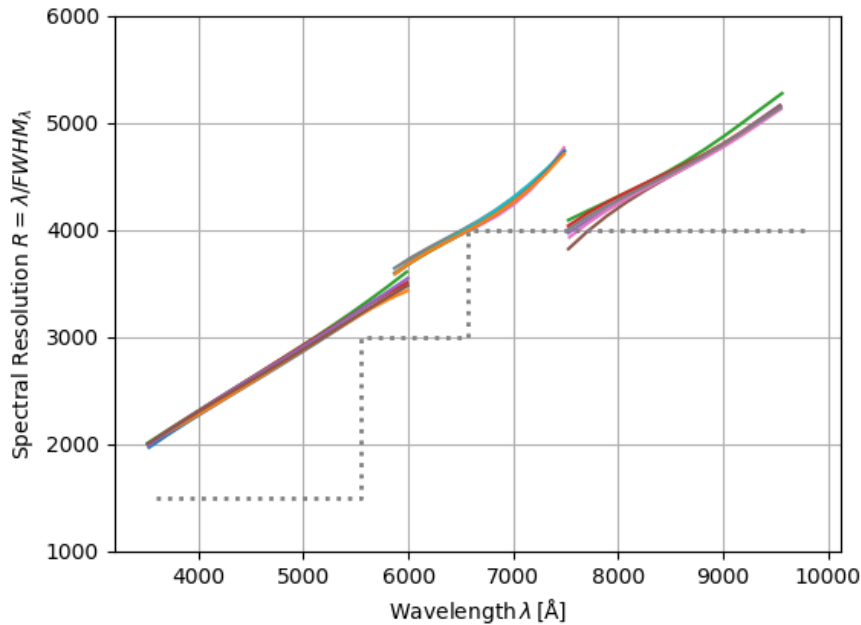


Figure 3: Measured resolution of the six installed spectrographs. Dotted lines are the system requirements. The as-built results match exquisitely to the modeled performance.

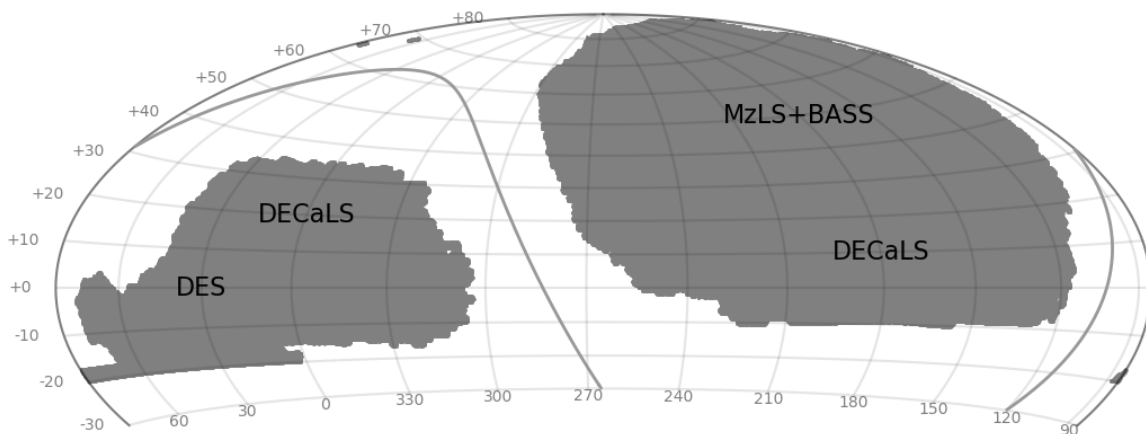


Figure 4: The planned DESI survey footprint is shown by the shaded area; it is built on several existing imaging surveys and extends as far south as $\delta = -20^\circ$ in the SGC and -10° in the NGC.

2 Beyond 2025 with DESI

Beyond the end of the first 5-year survey, DESI will remain a state-of-the-art facility for wide-field surveys. New commitments for funding will be required. But given the time scale to construct a facility more powerful than DESI and with no such project yet approved¹ we expect that the ground-based facility landscape in the second half of the 2020's will look much like the first. See Table 2 for a summary. We note that not only is DESI at the forefront of this generation, without it, the U.S. community will not have a facility to compete with ESO and Subaru. Further, we note that while Euclid and WFIRST will offer space-based platforms for slitless IR spectroscopy, optical spectroscopy remains a highly efficient way to get redshifts both at $z < 1.5$ and $z > 2$.

Key Science Goals: We anticipate that a second phase of DESI will continue to offer exciting survey opportunities. Certainly we will not have exhausted the supply of plausible targets on the sky. Imaging surveys from HSC, LSST, Euclid, SphereX, WFIRST, eROSITA, and others will yield improved isolation of valuable targets over areas of thousands to tens of thousands of deg². Spectroscopy can provide the key leverage to realize the science potential of these candidates, whether for redshifts or for more detailed characterization. DESI's combination of field of view, multiplex, throughput, and resolution makes it a great complement to the coming generation of imaging surveys.

There are at least 5 fertile areas of potential targets for such a survey:

- 1) High-redshift emission-line targets: improved selection of $1 < z < 1.6$ emission-line galaxies

¹We note that DESI (under the previous name BigBOSS) was identified in New Worlds New Horizons as an exemplar of the MidScale Innovation Program. Despite timely agency support (CD-0 approved in 2012 and CD-2 in 2015), non-federal funding to conduct long-lead procurements, and no major programmatic or technical interruptions, we will be in operations in 2020. We believe this is indicative of what projects of this complexity require, even in good outcomes!

Name	Telescope	# Fibers	FOV (deg ²)	Bandpass (nm)	Resolution
DESI	Mayall 4-m	5000	8	360–980	mid
PFS	Subaru 8-m	2400	1.5	380–1260	mid
4MOST	VISTA 4-m	2436	5	370–950	mid & high
WEAVE	WHT 4-m	960	3	370–960	mid & high
SDSS-V	Sloan & DuPont 2.5-m	1000	7	360–1700	mid (opt) & high (IR)

Table 2: A brief comparison of multi-fiber facilities under construction. Mid-resolution is typically a few thousand; high-resolution is typically around 20K, but for a more limited bandpass. DESI will offer the highest multiplex and largest field of view of these next-generation facilities; only PFS has more instantaneous light-gathering power, but it is not a dedicated platform. Of the current generation of facilities, LAMOST is operating 4000 fibers in a 20 deg² field of view, but with performance limited to bright galaxies and stars.

from deeper imaging; selection of Ly α emission candidates from deep imaging in the blue; or follow-up of low-quality emission-line candidates from Euclid and SPHEREx. Such a survey would increase the sampling of the large volume available at higher redshift.

2) Increased depth and sampling in the Lyman- α forest, reobserving known targets and adding fainter candidates from deeper imaging.

3) A high-density galaxy survey at $z < 1$, building on the DESI bright galaxy survey. These candidates are readily identified, but a high-density sample with precise spectroscopic redshifts would allow identification of groups and redshift-space distortions in the non-linear regime within the cosmic acceleration epoch.

4) A high-multiplex survey of the Milky Way, with $O(100)$ million stars, to yield radial velocities and stellar abundances to pair with the exquisite Gaia astrometry. The rapid reconfiguration time of DESI (< 2 minutes) makes short exposures an effective strategy.

5) Time-domain spectroscopy and transient host spectroscopy, building on SDSS-V and time-domain imaging surveys such as ZTF, LSST, and TESS.

Technical Drivers: While the DESI instrument could continue to be usefully operated in the same configuration as the pre-2025 phase, there may be opportunities for augmentations. Notably, the spectrographs are modular and could be altered or replaced, subject to cost and space constraints, if the adopted science goals called for it.

Organization, Status, and Schedule: A science collaboration for post-2025 operations has not yet been formed, but we expect that many of the current participants would be interested in continuing. The Mayall telescope remains property of the National Science Foundation, while the DESI equipment is DOE property.

We expect that planning for such surveys will pick up speed in 2021 with the arrival of early DESI data, which will solidify the on-sky performance and give a tactile sense of the target selections.

We note that there has been mention of the idea of moving DESI south to the Blanco in 2025. On the plus side, such a move would increase sky overlap with LSST. On the down side, it is an expensive proposition: it has taken over 1.5 years to install DESI at the Mayall, and much of that work would need to re-occur. We therefore expect that a move would result in substantial downtime for both telescopes, along with financial cost. Such a decision will require a detailed cost-benefit analysis. Given the large amount of near-equatorial sky visible jointly from Arizona and Chile, we suspect that many post-2025 survey options could be well performed without a move, potentially in collaboration with an instrument of similar or even lesser capability in the south.

Cost Estimate: The budget for a second phase of DESI operations would depend on the survey choices made as well as on the assessment of costs of ongoing instrument support, presumably informed by experience in the coming years of operations. However, the cost is likely $O(\$10 - 15)$ M/year (inclusive), comparable to those of other mid-scale facilities that deliver highly processed data products. Hence, we expect ongoing operations to fall in the Medium class

of ground-based activities.

In conclusion, we expect that the Mayall telescope with DESI will remain a world-class facility for high-multiplex optical mid-resolution spectroscopy in the latter half of this decade, offering the U.S. the opportunity to continue its leadership in spectroscopic wide-field surveys.

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