The Dark Energy Spectroscopic Instrument

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DESI Science Objectives

- Cosmic expansion accelerating
  - Breakdown of General Relativity?
  - New GR component giving repulsive gravity?
    - Is there time evolution?

- What measurements to perform?
  - The distance scale-redshift relation $D_A(z)$
  - Directly measure expansion rate $H(z)$
  - DESI will also look at the growth of structure
  - Cover evolution of these quantities over wide redshift range
    - A lot of interesting physics happening in range $0<z<3.5$

- What techniques?
  - Baryon acoustic oscillations
    - Provides robust metric to measure expansion history
    - Via tracer galaxies, can probe out to high redshift
  - Spectroscopy: precision in $3^{rd}$ dimension

No matter what: New Physics!!
DESI Science Requirements

• Maximize survey volume:
  — 9000 sq. degrees is threshold survey
  — Goal: baseline survey is 14,000 sq. degrees

• BAO distance scale measurement:
  — 0.28% precision (0 < z < 1.1)
  — 0.39% precision (1.1 < z < 1.9)

• Hubble Parameter to 1.05% at 1.9 < z < 3.7

• Need to extract $D_A(z)$ and $H(z)$ separately
  — In region $z < 1.5$, systematic uncertainties
    • < 0.16% $D_A$
    • < 0.26% for $H$
How Do We Get There?

- BOSS set very productive path
- Need 10x BOSS volume
How Do We Get There?

- BOSS set very productive path
- Need 10x BOSS volume
  - However, plug plates don’t scale past $O(10^6)$ sources/year
- Automated fiber positioning system
  - 5000 spectra/exposure
Figure 4.10: Proposed Fiber Cable cross section.

Figure 4.11: The routing of the Fiber Cable starts at the Focal Plane Spool Box, traverses the telescope tube and pivots, enters the spectrograph room, and terminates at the spectrograph spool box. Two routing options are shown with the one on the left preferred.
DESI System

- Cross Spider Cable
- Cable Junction Box Connection
- Main Cable(s)
- Cable Declination Pivot
- Fiber Support & Distribution
- Focal Plane & Actuators
- Cable Polar Pivot
- Spectrographs
- Slit Assemblies
DESI Prime Focus Corrector

- Field of view: 3.2°
- Wavelength bandpass: 360 – 980 nm
- f/3.6 900 kg glass
  - C3, C4 done
Focal Plate and Fiber Positioners

- 500 per petal: 10 petals in focal plane
- 5000 actuators on 800 mm diameter focal plate
- Need to be positioned within 5 micron of target
  — Fine tuning iteration < 1 minute
- Expect ~200k reconfigurations
Fiber Positioners

- brushless DC motor design
  - Design accuracy achieved
  - 10.4 mm
- Operation
  - center-to-center, 12 mm patrol disk
- In production
Petal Assembly

17x Fiber Conduits
Each carries 25 fibers.

7x Service Rails
Arrays of identical, alternating fiber and electrical breakouts.

40x Fiber / Wire Fanouts
Each serves up to 13 positioners + fiducials.

Positioner / Fiducial Power Supplies

Petal Alignment Pads

500x Fiber Positioner Envelopes

Slice Controller

Fiber Spool Bobs
Protects splice and handles transition to camera

GFA Power Supply

GFA Camera

10x Field

Petal

Positioner External Electronics

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Spectrographs

Prototype spectrograph undergoing evaluation

CCDs: 4096 x 4096, 15 µm pixel, 500 spectra

~140 mm
Spectrograph Requirements

Analysis includes:
- geometric blur
- fiber size
- diffraction
- CCD effects

**Spectral Resolution**

- Average
- Minimum
- Requirement

**Spot Size**

- Average
- Maximum
- 250µm Average
- 250µm Maximum
- Requirement

**Throughput**

- Blue Total
- Red Total
- NIR Total
- Sum
- Requirement
Dataflow – read data from spectrographs and store (FITS) images in disk archive

Control – orchestrate exposure sequence and control all components of the instrument

Monitor – monitor and record operational and environmental parameters

User Interface – observer console and remote access
DESI Online System

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DESI Survey Area & Imaging

- 14k sq. degree footprint
  - Low galactic and atmospheric extinction
  - Need new imaging in three primary areas

South:
- 6200 sq. deg.
- g, r, z bands
- Blanco/DECam

North:
- 5500 sq. deg.
- Mayall z band
- Bok g, r bands

g=24.0, r=23.6, z=23.0
~ 2 mag deeper than SDSS

Public data releases
- Started early 2015
DESI Collaboration

Expertise includes:
- BOSS, DES, LSST
- FMOS, LAMOST
- VIMOS, Megacam
- WFIRST, JDEM
- ROTSE, GTC Nasmyth

484 Collaborators
- 31 US Universities
- 5 DOE Laboratories
- 41 foreign institutions
**Timeline**

- **Deconstruction of Mayall:** Oct. 2017
  - Corrector installation Feb. 2018

- **Commissioning starts:** Oct. 2018

- **Survey begins** Apr. 2019
  - 1st data set defined Apr. 2020
  - BAO results on 1st data Nov. 2020
    - Expected to be at DETF Stage IV level

- **BAO results on 60% data** Nov. 2022
  - Surpass science requirements

- **Survey ends** Apr. 2024
  - Final BAO results Oct. 2024
DESI Science Program

• Broad array of science planned
  — GR cosmology constraints
  — Discriminating non-GR models
  — Inflation
  — Neutrino constraints

• Precision measurements
  — 2x to 6x Planck + BOSS BAO rms

• auxiliary programs in:
  — Galactic physics
  — Time-domain science

Figure 2.10: Expansion rate of the Universe as a function of redshift. In the upper plot, the filled blue circle is the $H_0$ measurement of [106], the solid black square shows the SDSS BAO measurement of [107], the red square shows the BOSS galaxy BAO measurement of [6], the red circle shows the BOSS Ly-$\alpha$ forest BAO measurement of [47], and the red x shows the BOSS Ly-$\alpha$ forest BAO-quasar cross-correlation measurement of [108]. The lower plot shows projected DESI points.

Figure 2.11: The $w_0-w_a$ plane showing projected limits (68%) from DESI using just BAO and using the broadband (BB) power spectrum. Also shown is the limit from BOSS BAO. Planck priors are included in all cases, and DESI includes the BGS and non-redundant part of BOSS. The figure of merit of the surveys is inversely proportional to the areas of the error ellipses.
**DESI Hubble Diagram**

<table>
<thead>
<tr>
<th>Target type</th>
<th>z range</th>
<th>Target density deg^2</th>
<th>Good z density deg^2</th>
<th>Δz/(1+z) precision</th>
<th>Δz/(1+z) systematic</th>
<th>Bad z assignment</th>
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<td>&lt; 5%</td>
<td>&gt; 95%</td>
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<td>120</td>
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<td>-</td>
<td>&lt; 2%</td>
<td>&gt; 72%</td>
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DESI provides unique History of expansion
Unprecedented accuracy
BAO Distance Scale Measurement

- DESI is a substantial step forward
  - 10x inverse variance on BOSS

- DESI nearly optimal ground based experiment:
  - all of the non-dusty sky available
  - easiest galaxies for $z$ measurement

- competitive with Euclid
  - Large redshift range
  - Extend overall range to higher $z$

Low systematic uncertainties:
- statistics dominated
DESI Will Discriminate Between Dark Energy Models

Alternative Universes for constant $w$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$

- $w = -1.03$
- $w = -0.97$

past $\leftarrow$ today $\rightarrow$ future

Billions of Years from Today

Redshift

Scale of the Universe Relative to Today's Scale
DESI Science Reach

- Modified gravity: \( f\sigma_8 \) to 0.35%

![Graph showing error improvements over Planck + BOSS BAO](chart.png)
DESI measures the total neutrino mass

- Large-scale structure (LSS) is sensitive to neutrino properties
- Massive neutrinos decrease small-scale power at low redshift
  — DESI can measure an error of 0.017 eV in the sum of masses, enough to start to distinguish the normal and inverted hierarchy of mass states
Synergies with Other Surveys

- **WL surveys**
  - Systematics
  - Photo-z calibrations, source of significant sys. error

- **Euclid/WFIRST**
  - Wider redshift range
  - Different techniques to get at tracer populations

- **SN surveys**
  - Wide redshift coverage overlaps range

- **CMB surveys**
  - DESI needs Planck to calibrate the BAO scale
  - CMB Stage-IV needs DESI to achieve their neutrino mass constraints

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Figure 2.16: Constraint on the sum of the neutrino masses in eV against the dark energy density $\Omega_{DE}$ obtained by combining DESI BAO with LSST weak lensing, in each case including Planck CMB constraints. More powerful constraints are obtained when the full power spectrum from DESI is used. See Table 2.11.

Figure 2.17: Prospective constraints in the $\Omega_{m}$–$\Omega_{\Lambda}$ plane obtained by combining DESI BAO with LSST weak lensing. More powerful constraints are obtained when the full power spectrum from DESI is used. See Table 2.9.

Redshifts for many tens of thousands of SNe host galaxies. This will happen both for the faint galaxy survey out to $z \sim 1$, but also with the BGS at $z < 0.4$. Over a 10-year period, a typical ($L_{\ast}$) galaxy has at least a 1% probability of having a detectable SN Ia. This means that the BGS will contain of order $10^5$ supernova host galaxies, and the LRG sample of more massive galaxies could produce a comparable number at higher redshift. While photometric redshifts are planned for the large LSST and DESI supernova samples, spectroscopic redshifts allow more precision, particularly at...
Status and Plans

• DESI inherits from pioneering current and prior surveys
  — Will nearly complete northern sky BAO to $z \sim 1.5$
  — Unprecedented precision of key cosmological parameters

• Design finalized and passed thru CD-3
  — Strong support from DOE and HEP community
  — Substantial private (non-DOE) funding
    • Eg. lenses, prototype spectrograph

• All major elements well along in construction, development
  — Imaging surveys
  — Instrumentation: CCDs, fibers and positioners, lenses
  — Software systems

• Commissioning on target for 2018
• First science data in 2 years! Stay tuned!!!