DESI: Dark Energy Spectroscopic Instrument

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How We Know there is Dark Energy

Expansion History of the Universe


Clustering Search (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)
Tonry et al. (2003)

Mikajulis et al. (2007)
Astier et al. (2006)
Knop et al. (2003) (SCP)
Amanullah et al. (2008) (SCP)
Barris et al. (2004)
Perlmutter et al. (1999) (SCP)
Riess et al. (1999) + HST
Holtzman et al. (2009)

Contreras et al. (2010)
Hicken et al. (2009)
Kowalski et al. (2008) (SCP)
Jha et al. (2006)
Riess et al. (1999)
Caldwell et al. (2003)
Hamuy et al. (1996)

After inflation, the expansion either...

- fast decelerated, then accelerated
- or always decelerated

Exceeds forever
Collapses

After inflation, the expansion either...
$\frac{\ddot{a}}{a} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3}(\rho + 3p)$

$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$

$a$ is the size-scale of the universe relative to size today
Making the Universe Collapse

\[ v = Hr \]
\[ H = h \times 100 \text{(km/sec)/Mpc} \]
\[ h \approx 0.7 \]

Zero total energy. Just enough to stop expansion.
Energy Budget of the Universe

- Re-write Friedmann-Lemaitre equation:

\[ \Omega_m + \Omega_{\text{rad}} + \Omega_\Lambda + \Omega_k = 1 \]

\[ \Omega_m = \frac{\rho_m}{\rho_{\text{crit}}} \quad \Omega_{\text{rad}} = \frac{\rho_{\text{rad}}}{\rho_{\text{crit}}} \quad \Omega_\Lambda = \frac{\rho_\Lambda}{\rho_{\text{crit}}} \quad \Omega_k = -\frac{k}{H_0^2} \]

\[ H(a) = \frac{\dot{a}}{a} = H_0 \sqrt{a^{-4} \Omega_{\text{rad}} + a^{-3} \Omega_m + a^{-2} \Omega_k + a^{-\epsilon} \Omega_{\text{DE}}} \]

\[ D(a) = \int_a^1 \frac{da'}{a'^2 H(a')} = \int_0^z \frac{dz'}{H(z')} \]

distance
Dark Energy Equation of State

\[ w(a) = \frac{p}{\rho} \]

From Friedmann-Lemaître Equations

\[
\frac{d\rho}{dt} = -3(1 + w(a))\rho \frac{da}{dt} \quad \rho(a) = \rho(a = 1)e^{\int^{1}_{a} \frac{1}{a(1+w(a))} da} 
\]

Matter: \( w=0 \)  \hspace{1cm} Radiation: \( w=1/3 \)  \hspace{1cm} Cosmological constant: \( w=-1 \)

Accelerating Universe means \( w < -1/3 \) or General Relativity fails.
Dark Matter vs Dark Energy

Scale-size of universe = $a$

- **Matter**: $\rho \propto a^{-3}$
- **Radiation**: $\rho \propto a^{-4}$
- **Dark Energy**: $\rho \propto a^0$
Energy Budget of Universe

• Combining three kinds of measurements we learn that
  – The Universe is flat.
  – 32% of energy is matter.
  – 68% of energy is “dark”.

• Distribution of elements tells us only 5% of energy is ordinary matter.
  – 27% of energy is due to “dark matter”
How Hard is it to Rule out Cosmological Constant?

![Graph showing the relationship between scale of the universe relative to today's scale and time in billions of years from today. The graph includes data points for SNe (binned), BOSS, and MS-DESI (predicted) with annotations for different cosmological models.]
Tiny Ripples in Early Universe

Ripples in early universe imprint standard ruler in cosmic microwave background

Cosmic Microwave Background

COBE, WMAP, Planck

θ
BAO gives Ruler

That pattern is preserved in the distribution of the galaxies.

By measuring the pattern looking back billions of years we can deduce the expansion history of the universe.

BAO at z=0.57
Anderson et al (2012)
CMB is 2-d  BAO is 3-d

BAO standard ruler from Planck
\[ \theta_s = 0.596724 \pm 0.00038 \text{ deg} \]

BAO standard ruler from BOSS & DESI
How BAO Works

(c/H)Δz radial
Δθ angular

BAO first detection plot
Eisenstein et al (2005)
Best BAO so Far: BOSS
Lyman-alpha forest: First dark energy results $z>2$

Forest of absorption lines maps location of neutral hydrogen along line-of-sight from quasar.

Light absorbed when stretched to 121.6 nm.

BOSS

BAO at $z=2.3$
Busca et al (2013)
Slosar et al (2013)
BOSS Lyman-alpha Sees Deceleration!

\[ \frac{H(z)}{(1+z)} \text{ (km/s/Mpc)} \]

- $H_0$
- SDSS
- BOSS Ly-alpha
- BOSS galaxies

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From BOSS to DESI

- Scale up BOSS to a massively parallel fiber-fed spectrometer
- Broad range of target classes: LRG’s, ELG’s, QSO’s
- Broad redshift range: $0.5 < z < 1.6$, $2.2 < z < 3.5$ \{region between $0.7 – 1.6$ new\}
- Sky area: 14,000 square degrees
- Number of redshifts: 24 million
- Medium resolution spectroscopy, $R \approx 4000$
- Spectroscopy from blue to NIR: $360 \text{ nm} < z < 980 \text{ nm}$
- Automated fiber system, $N_{fiber} \approx 5000$
- Up to 5 year DE survey
DESI Hardware & Software Elements

**Focal Plate**

**Targets**

**Data Management**

**Prime Focus Corrector**

**Spectrometer**

**Fiber Positioner**
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**Fiber System**

**CCD's**
Galaxy Targets

<table>
<thead>
<tr>
<th>Galaxy type</th>
<th>Redshift range</th>
<th>Bands used</th>
<th>Targets per deg$^2$</th>
<th>Exposures per deg$^2$</th>
<th>Good z’s per deg$^2$</th>
<th>Net sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>LRG</td>
<td>0.4–1.0</td>
<td>$r,z,W1$</td>
<td>350</td>
<td>700</td>
<td>300</td>
<td>4.2 M</td>
</tr>
<tr>
<td>ELG</td>
<td>0.7–1.6</td>
<td>$g,r,z$</td>
<td>2300</td>
<td>2300</td>
<td>1400</td>
<td>19.6 M</td>
</tr>
<tr>
<td>QSO (tracers)</td>
<td>0.9–2.2</td>
<td>$g,r,z,W1,W2$</td>
<td>175</td>
<td>175</td>
<td>100</td>
<td>1.4 M</td>
</tr>
<tr>
<td>QSO (Ly-α)</td>
<td>&gt; 2.2</td>
<td>$g,r,z,W1,W2$</td>
<td>75</td>
<td>200</td>
<td>40</td>
<td>0.6 M</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>2900</td>
<td>3375</td>
<td>1840</td>
<td>25.8 M</td>
</tr>
</tbody>
</table>

Select photometrically, measure spectroscopically.
[O II] doublet \( Z=1.34 \)

QSO – Lyman–alpha forest

LRGs

\begin{align*}
D_{3/2}^{3/2} & \rightarrow 4S_{3/2}^{3/2} \\
D_{5/2}^{5/2} & \rightarrow 4S_{3/2}^{3/2}
\end{align*}
Measure Two-Point Correlation as Function of $z$

\[ r^2 \xi(r) \]

BOSS

$$\alpha = 1.016 \pm 0.017$$
$$\chi^2 = 30.53/39 \text{ dof}$$
Anticipated Quality of DESI Expansion Measurements

\[ H(z)/(1+z) \text{ (km/s/Mpc)} \]

- **galaxies**
- **Lyman-alpha**

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DESI Achieves Space-Based Precision

![Graph showing distance scale error vs. redshift for BOSS, WFIRST-2.4, MS-DESI, and EUCLID. The graph displays a decline in distance scale error with increasing redshift. BOSS has the highest initial error but shows a significant decrease, while WFIRST-2.4 has a lower initial error and maintains a constant level. MS-DESI and EUCLID start with similar errors, with MS-DESI showing a slight increase at redshift 2.5.]

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The Wiener (1930)-Khinchin (1934) Theorem – naive version due to Einstein (1914):

- “The Fourier transform of the correlation function is the power spectrum”

\[
\langle \rho(k)\rho^*(k') \rangle = \left\langle \int dx e^{ikx} dx' e^{-ik'x'} \rho(x)\rho(x') \right\rangle = \left\langle \int dx e^{ikx} dx' e^{-ik'x'} \xi(x-x') \right\rangle 
= \int dx e^{i(k-k')x} dx' e^{-i(k'-k)x} \xi(x-x') = 2\pi\delta(k-k')\bar{\xi}(k')
\]
DESI: Not just BAO

Power spectrum is Fourier transform of two-point correlation function.

Power spectrum tests:
- General Relativity
- Inflation
- Number of neutrinos
- Sum of the neutrino masses

\[ n_s : \pm 0.0022 \]
\[ \alpha_s : \pm 0.0024 \]
\[ \Sigma m_\nu : \pm 0.024 \text{eV} \]
\[ \Sigma N_\nu : \pm 0.056 \]
Measuring the sum of neutrino masses

\[ \Delta m_{32}^2 = 2.32 \times 10^{-3} \text{ eV}^2 \]
\[ \Delta m_{21}^2 = 7.50 \times 10^{-5} \text{ eV}^2 \]

<table>
<thead>
<tr>
<th>Data</th>
<th>( \sigma_{\Sigma m}) [eV]</th>
<th>( \sigma_{N_{\nu,\text{eff}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck</td>
<td>0.350</td>
<td>0.18</td>
</tr>
<tr>
<td>Planck+DESI BAO</td>
<td>0.090</td>
<td>0.18</td>
</tr>
<tr>
<td>Gal (( k_{\text{max}} = 0.1 ))</td>
<td>0.024</td>
<td>0.13</td>
</tr>
<tr>
<td>Gal (( k_{\text{max}} = 0.2 ))</td>
<td>0.017</td>
<td>0.084</td>
</tr>
<tr>
<td>Ly-( \alpha ) forest</td>
<td>0.039</td>
<td>0.11</td>
</tr>
<tr>
<td>Ly-( \alpha ) forest + Gal (( k_{\text{max}} = 0.2 ))</td>
<td>0.017</td>
<td>0.063</td>
</tr>
</tbody>
</table>
Redshift Space Distortion

• Can’t measure distance directly.
• Mismeasure if there is “peculiar velocity”

Assume $\vec{v} = H r \hat{n}$ along line of sight
so peculiar velocity $\Delta \vec{v}$ leads to shift
$\Delta r \hat{n} = \Delta \vec{v} \cdot n \hat{n} \hat{n} / H(a)$

• Gravity will amplify all density perturbations.

$$\delta \rho(t) = D(t) \delta \rho(t = 0) \quad [\text{now}]$$
Galaxies vs Matter

• Assume fractional fluctuation in galaxy density is proportional to fractional fluctuation in matter:

\[ \delta_{\text{galaxy}} \equiv \frac{\delta \rho_{\text{galaxy}}}{\bar{\rho}_{\text{galaxy}}} = b \frac{\delta \rho_{\text{matter}}}{\bar{\rho}_{\text{matter}}} = b \delta_{\text{matter}} \]

Because we observe in redshift space, there is a distortion of the power spectrum:

\[ P(\vec{k})_{\text{galaxy, RSD}} = (b^2 + (\hat{k} \cdot \hat{n})^2 f)^2 P(k)_{\text{matter, realspace}} \]

\[ f = \frac{d \ln D}{d \ln a} \]
Redshift Space Distortion at BOSS

Line of sight

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Testing General Relativity

- The growth function $D(a)$ is determined by the matter density and General Relativity.

In practice, we measure $f\sigma_8$, where $\sigma_8$ sets the scale for $P(k)$. There will be 2% measurements of $f\sigma_8$ at many values of $z$. 
Inflation

- Look at power spectrum
- Look for three-point correlations (CMB)
- Look a “scale dependence” of bias

\[ P(k) = P(k_0)(k / k_0)^{n_S(k_0) + \frac{1}{2}\alpha_S \ln(k/k_0)} \]

<table>
<thead>
<tr>
<th>Data</th>
<th>( \sigma_{n_S} )</th>
<th>( \sigma_{\alpha_S} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gal ( (k_{\text{max}} = 0.1 , h^{-1}\text{Mpc}) )</td>
<td>0.0024 (1.6)</td>
<td>0.0051 (1.1)</td>
</tr>
<tr>
<td>Gal ( (k_{\text{max}} = 0.2 , h^{-1}\text{Mpc}) )</td>
<td>0.0022 (1.7)</td>
<td>0.0040 (1.3)</td>
</tr>
<tr>
<td>Ly-( \alpha ) forest</td>
<td>0.0029 (1.3)</td>
<td>0.0027 (2.0)</td>
</tr>
<tr>
<td>Ly-( \alpha ) forest + Gal ( (k_{\text{max}} = 0.2) )</td>
<td>0.0019 (2.0)</td>
<td>0.0020 (2.7)</td>
</tr>
</tbody>
</table>

Planck:
\( n_S = 0.9614 \pm 0.0063 \)
\( \alpha_S = -0.015 \pm 0.017 \)
DESI Improves Many Measurements

**Improvement factors**

- $w_p$: $\sigma = 0.023$
- $w'$: $\sigma = 0.28$
- $\omega_k$: $\sigma = 3.6 \times 10^{-4}$
- $\Sigma m_v$: $\sigma = 0.09$
- $n_s$: $\sigma = 3.8 \times 10^{-3}$
- $\alpha_s$: $\sigma = 2 \times 10^{-3}$
- $N_{V,I}$: $\sigma = 0.063$

**Legend:**
- DESI galaxy and LyaF BAO
- +galaxy broadband $k < 0.2 \, \text{h/Mpc}$
- +LyaF broadband

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Price Tag

$2.50
Summary

• DESI: best dark energy information @ 2020
• Modest experiment using existing telescope
• Based on successful BOSS experiment
• Not just dark energy, but GR, inflation, neutrinos