BigBOSS

Michael Levi
October 16, 2012
Fermilab PAC
August 2012 – The Dark Energy Science Report aka Rocky-III

- Recommends Stage IV BAO + RSD experiment in 2017-2022 timeframe
- DOE responds w/ CD-0

“There is compelling case for an advanced wide-field spectroscopic survey, which would enable dark-energy information at the Stage IV level through the techniques of Baryon Acoustic Oscillations and Redshift Space Distortions. A spectroscopic survey would produce important dark-energy science results in the period between the completion of the Stage III Dark Energy Survey (DES) photometric project and the arrival of results from the Stage IV LSST photometric project.”
BigBOSS Introduction

• BOSS is a Stage III BAO experiment
  — Highest significance BAO detection to date (~6.7 sigma)
  — Highest precision BAO distance measurements (1.7%) to date.
  — Redshift Space Distortion measurement
  — Proving Lyman-alpha forest technique
  — Stage III Dark Energy Experiment

• BigBOSS will improve on BOSS by an order of magnitude.
  — Ambitious project, competitive with space-based BAO missions.
  — Fulfills the DOE CD-0 mission need for a spectroscopic survey
  — Successfully reviewed by DoE and national panels.
  — Nearing completion of international 3-year R&D program
  — High state of technical readiness
  — Built upon BOSS collaboration, 35 international institutions

BigBOSS will be the first Stage-IV dark energy experiment in the world.
BigBOSS Collaboration

US Members:
Brookhaven National Laboratory, Carnegie Mellon University, Fermi National Accelerator Laboratory, Johns Hopkins University, Lawrence Berkeley National Laboratory, National Optical Astronomy Observatory, New York University, The Ohio State University, SLAC National Accelerator Laboratory, University of California, Berkeley, University of Kansas, University of Michigan, University of Pittsburgh, University of Utah, Yale University.

International Institutions:
Ewha Womans University, Korea; French Participation Group (APC, IAP- Paris; CPP, CPT, LAP Marseille; CEA, IRFU – Saclay); Goettigen Univ, Spanish Participation Group (IAA, Granada; IAC, Tenerife; ICC, Barcelona; IFT, Madrid; U. Valencia); Shanghai Astronomical Observatory, UK Participation Group (Durham, Edinburgh, UC London, Portsmouth); University of Science and Technology of China.

... and growing!
BigBOSS – Status

• Conceived in 2009.
• Presented to HEPAP/PASAG 2009
  — “substantial immediate support” for BigBOSS R&D to achieve “timely planning of a coherent ground-space dark energy experiment”
  — Start of R&D
• White paper submitted to Astro2010; held up as an exemplar of mid-scale projects
• October 2010 competitive proposal to NOAO Large Science Programs
  — Non-advocate review led by Brian Schmidt: “the resulting survey would be one of the telescope’s major scientific contributions”.
  — Awarded 500 nights on the Kitt Peak 4-m
• Proposal submitted to DoE in 2011; successfully reviewed in December
  — “compelling case”… “competitive with space based missions”
  — “Due to the maturity of the collaboration and design, critical decision 1 (CD-1) approval could quickly follow.”
• Collaboration requests construction start in 2014, first data would be in 2017.
BAO
What are Baryon Acoustic Oscillations (BAO)?

- The plasma of the early Universe supports sound waves
  - Speed of sound $\sim c/\sqrt{3}$
  - Sound wave stalls, leaving imprint on density fluctuations.
  - Characteristic scale of 153.2 Mpc $\sim 4.7\times10^24$ m
  - Density fluctuations are amplified under gravity, sites for galaxies
BOSS measures the BAO standard ruler using the distribution of galaxies

BOSS results with 1/3 of Data; on track for 1% distance measurements at 2 redshifts
BOSS measures the BAO standard ruler using the line-of-sight distribution of hydrogen

First results from BOSS Lyman-alpha at $z=2.3$

BOSS collaboration succeeds with high-$z$ Lyman-alpha for BAO

Lyman-$\alpha$ forest technique uses line-of-sight absorption from back-lit quasar (QSO)

Will show that the Universe was decelerating before it accelerated!
Anticipated Stage III DE FOM

BOSS dark energy will achieve Stage III Figure of Merit with galaxy BAO Figure of Merit comparable to sum of techniques in Dark Energy Survey (DES)

Does not include Lyman-alpha forest or redshift space distortion measurements.

DETF figure of merit = inverse area of ellipse
\[ w(z) = w_0 + w_a(1-a) \]
Science Goals
BigBOSS is BIG

SDSS ~ $2h^{-3}\text{Gpc}^3$  $\rightarrow$  BOSS ~ $6h^{-3}\text{Gpc}^3$  $\rightarrow$  BigBOSS ~ $50h^{-3}\text{Gpc}^3$
BigBOSS Science Goals

DETF Stage IV - Figure of Merit $\times 10$ over Stage-II

Sub-1% distance error

$\sim 1\%$ error on $f\sigma_8$ (growth rate)

Additional goals for $H(z)$, $P(k)$, spectral index, and total neutrino mass

NASA WFIRST Science Definition Team
• Recommends Stage IV BAO + RSD experiment in 2017-2022 timeframe

• Must be ambitious in order to achieve Stage-IV
  — BigBOSS was designed to satisfy Stage-IV BAO
  — BAO Hubble Diagram up to redshift $z \sim 3.5$
  — BOSS FOM = 30
  — BigBOSS FOM = 700, Gravity-FOM= 2500, $\sigma(\Sigma m_\nu) \sim 0.024\text{eV}$

• Three elements necessary:
  — Requires dedicated telescope dark time
  — Imaging data for target selection
  — Project ready for 2017 start
Telescope
Mayall Telescope

- 3.8m Diameter
- Located at Kitt Peak, AZ
- Operated by AURA/NOAO
- Compatible with wide-field corrector optics to achieve 7.1-degree$^2$ field of view
- 7 deg$^2$ field of view is excellent match to LSST
## Investigated Siting Options

<table>
<thead>
<tr>
<th>Name</th>
<th>Site</th>
<th>Notes and Exclusions</th>
<th>M1 f/#</th>
<th>M1 Diam. (m)</th>
<th>f/#</th>
<th>f (m)</th>
<th>Suitable for BigBOSS 3-degree corrector?</th>
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<td>marginal</td>
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<td>NIR</td>
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</table>
Mayall is still available for dedicated survey

• NOAO call for proposals in 2010, BigBOSS responded and was awarded 500 nights on the Mayall telescope.

• Continuing opportunity for a dedicated survey thanks to the NSF/AST Portfolio review.
  — “While we recommend ending operation of the Mayall as a user facility, this would not preclude its operation as a dedicated survey facility with funds from the competed MSIP and/or outside agencies. [p133]

• AURA incredibly supportive of BigBOSS on the Mayall:
  — "The Mayall remains one of the most productive ground-based facilities, with the highest impact per dollar ratio of any OIR telescope. The Mayall will only grow more important as it transitions to hosting the BigBOSS dark energy survey, a collaborative project between NOAO, NSF, the Department of Energy, and the US astronomical community."
Imaging – Target Selection
Three target categories:
1. Luminous Red Galaxies (LRGs) \( z = 0.5 \rightarrow 1 \)
2. Emission Line Galaxies (ELGs) \( z = 0.5 \rightarrow 1.6 \)
3. QSOs \( z = 0.5 \rightarrow 3.5 \)

Simple set of cuts to select targets from imaging data: g, and R-band to 23.5 mag
End-to-end target selection has been verified with real data

Targeting sources:
- SDSS imaging (complete over 11,000 deg\(^2\))
- WISE satellite (complete over full-sky)
- PTF-1 (R-band data to 5,000 deg\(^2\))
- iPTF (g-band data to 5,000 deg\(^2\))
- PTF-2 aka ZTF (17,000 deg\(^2\))
- PanSTARRS (27,000 deg\(^2\))

Currently, much more targeting data available in the Northern Hemisphere. 14,000 square degrees will be available for BigBOSS
Zwicky Transient Factory

- Significant upgrade to the Palomar Oschin Schmidt focal plane
- ZTF can perform the BigBOSS LRG/ELG target selection in 2 filters in 1 year
- Project led by Caltech; chips already being fabricated (e2V)
- On-sky 2015, agreement to deliver data to BigBOSS

<table>
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<tr>
<th>Telescope</th>
<th>ΩΩΩ</th>
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<td>iPTF/PTF</td>
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<td>DES</td>
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<td>ZTF</td>
<td>46.5</td>
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<tr>
<td>LSST</td>
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Technical Status
A photon’s path through the BigBOSS instrument:

- 4m primary class telescope (KPNO)
- 7° corrector (FNAL, UK)
- Focal plane (Spain)
- 5000 fiber Actuators (China, LBL, Spain)
- Fiber System (LBL, UK)
- Spectrographs (France)
- Dewars/Cryogenics (Saclay)
- Detectors (LBL, FNAL)
- DAQ (Ohio)
- Computing (NERSC, NYU, Utah)
- Guiding (SLAC)
- Alignment (Yale)
- Calibration (U. Michigan)
BOSS Plugplate Timelapse
Technical Innovations

- 7 deg$^2$ field-of-view (new corrector optics for the telescope)
- Robotic fiber positioners
- High throughput spectrograph
  - Compact
  - Captures all the light from the fiber
  - Determines redshifts over broad range
- New Volume-Phase Holographic Gratings
  - For blue sensitivity (need for critical Lyman-$\alpha$ targets)
- “Super-red” sensitive CCD’s (higher QE than BOSS devices)
- Compact/inexpensive cryogenic system
Technical Strategy

• Science requirements of BigBOSS similar to BOSS, just bigger!

• Copy BOSS, it works! Plus, extensive code base, plus BAO collaboration.

• Technical goals are: All about attaining high throughput
  — Sky-noise dominated, loss of signal in fiber, means square-law time

• Most expensive element is spectrograph

• Critical path is spectrograph
Dec. 2011 DOE Review of BigBOSS

- R&D funded in China, France, Spain, U.K. following separate processes
- After 3-years of R&D, reviewers agree BigBOSS is ready to proceed.

“In summary, the panel believed that the R&D plan will lead to a mature technical design within 18 months. The panel found that the management team is clearly ready to move ahead with the project as soon as the external hurdles are cleared, including the telescope availability, and roles and responsibilities of the lead laboratories and funding agencies. The management should work with the stakeholders and agencies to bring BigBOSS to a condition where CD-0 approval can be requested expeditiously. Due to the maturity of the collaboration and design, critical decision 1 (CD-1) approval could quickly follow.”
Spectrographs
Spectrograph

- 10 spectrographs, 500 fibers each
- 3-arms 360nm – 980nm
- Cryo-cooler
- BOSS heritage LBNL CCDs + “super-red”
- Similar in design to BOSS (Smee, etal)
- Up to R ~ 5500
Spectrograph Properties

- Critical design input from BOSS data
- Compact ~6” diameter
- Easy to integrate with cryogenics+detectors
- f/1.75 design is very modest optical concept, compatible with our reduced diffusion, full-depletion CCD’s.

Throughput

Spectral Resolution
BigBOSS Cryostat (France)

- CCD Temperature within +/-1K; stability within 0.3K

BigBOSS cryostat test Bench: vessel and cryocooler
CCD’s

- Using BOSS CCD design (low noise, high QE)
- Packaging effort at FNAL — SiDET
- “super-red” sensitive
- Low charge diffusion variant
Fiber Positioners and Fiber System
LAMOST (China) Focal Plane
4000 actuators
Fiber Positioners

• **Results**

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<tr>
<th></th>
<th>R [µm]</th>
<th>θ [µm]</th>
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<tr>
<td>Absolute Accuracy</td>
<td>5.6</td>
<td>7.0</td>
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<tr>
<td>Repeatability</td>
<td>± 3.6</td>
<td>± 3.2</td>
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</table>

Step Size 1.0 ± 0.5  
1.2 ± 0.6

- LBL
- China
- Spain
Fiber Positioning in BigBOSS
Corrector
New $7^0 \text{ deg}^2$ FOV Corrector

- New optical concept with ADC
  - Corrector ingests light at F/2.8, outputs at F/4.5
Widefield prime focus corrector

— New and improved corrector concept (since proposal)
  • Improved geometric blur (<20μm rms over 550-980nm)
    — 450-550nm: 0.54 arcsec FWHM
    — 450-980nm: 0.47 arcsec FWHM
    — 550-980nm: 0.43 arcsec FWHM
  • Reduced mass (-365kg)
  • Better fiber coupling (chief ray normal deviation <0.6°)
  • Tolerancing and compensation study completed
  • Industry cost & manufacturing study completed
• FNAL is doing a full FEA analysis of the corrector and hexapod configuration.

• Current design satisfies spec.
R&D Started in 2009

Simplified Schedule

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<td>CD-0</td>
<td>CD-1</td>
<td>CD-2/3a</td>
<td>CD-3b</td>
<td>Start of Installation</td>
<td>Start of Commission</td>
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<td>pre-Concept</td>
<td>Concept</td>
<td>Prel Des</td>
<td>Final Des</td>
<td>Fabrication</td>
<td>Assembly and Test</td>
<td>Operation</td>
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<td>FY12 and FY13 R&amp;D Activity</td>
<td>Prel Design</td>
<td>Final</td>
<td>Procure</td>
<td>*Grind &amp; Polish</td>
<td>*Align *</td>
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<td>Assm</td>
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<td>Acc. Test</td>
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Critical Path

R&D Started in 2009
Dedicated surveys get the job done! Good utilization of an expensive instrument.

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<tr>
<th>Instrument</th>
<th>Telescope</th>
<th>Ref</th>
<th>Nights / year</th>
<th>No. Galaxies</th>
<th>sq deg</th>
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<td>85K LRG</td>
<td>7600</td>
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<td>239K</td>
<td>1000</td>
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<td>1.4M LRG + 160K Ly-α</td>
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</table>

4 Hill et al ASP Conf Series vol 399, 115 (2008) ** but 1/7 fill factor
5 Schlegel et al arXiv 1106.1706 (2011)
6 Ellis et al arXiv 1206.0737 (2012)
7 de Jong et al arXiv 1206.6885 (2012); primarily GAIA follow-up
Executive Summary

- **BigBOSS science is Stage-IV BAO**
  - x10 BOSS, an ambitious project!

- **Recommendation of Rocky-III requires:**
  - Dedicated access (100 dark nights/year or more) on a 4m telescope
  - Imaging for targets (14K square degrees or more)
  - Project ready to proceed now and complete before LSST, Euclid

- **Extensive planning process completed with AURA/NOAO**
  - Selected by NOAO through competitive process

- **Imaging Data Available**
  - PTF, ZTF, etc…

- **High State of Technical Readiness**
  - Expanded BOSS Collaboration, International collaboration
  - 3 years of R&D, heavily reviewed, panels agree we are ready
FNAL & BigBOSS

• FNAL:
  — Critical role in BigBOSS, essential for project success!
  
  — Brings unique expertise on:
    • Corrector barrel and hexapod design & fabrication
      — FNAL effort led by Gaston Gutierrez
    • CCD packaging & testing (SiDET)
      — FNAL effort led by Juan Estrada
BigBOSS Conclusions

• Perform state-of-the-art test of Dark Energy using Baryon Acoustic Oscillations (BAO/RSD) as a standard ruler to chart expansion history of Universe
  — Designed from the start to be a Stage-IV BAO/RSD experiment
  — Will be the first Stage-IV dark energy experiment, 2017-2022.
  — Fully competitive with proposed European satellite mission EUCLID (BAO)
  — Will retain US leadership
  — R&D nearing completion
  — Will overlap DES and LSST footprints
  — BigBOSS can move to southern hemisphere to twin 4m telescope in ~2022 when the Blanco may become available
Backup Slides
The Standard Ruler in the Galaxy Correlation Function

Imprint of sound waves frozen in the early Universe

Scale set by sound horizon = 153.2 ± 1.7 Mpc

Standard ruler analogous to standard candles

Galaxy Separation (Mpc = 3.08e22 m)
Baryon Acoustic Oscillations (BAO)

BAO measures 2 geometrical rulers:
- angular diameter distance \((d_A)\)
- line-of-sight (Hubble constant)

Implements \textit{linearly} with \textit{Survey Area, Number of Galaxies,} \(\sqrt{\text{Volume}}\)

\(\Delta r_{\parallel} = (c/H) \Delta z\)
\(\Delta r_{\perp} = D_A \Delta \theta\)

\(\Delta z = 0.2\) over 10,000 deg

1% measure

\(H(z)\) and \(d_A\)
Redshift Space Distortions

• Observed redshift depends on both Hubble expansion and additional “peculiar velocity

• Galaxies move because cosmological structure is growing

• Resulting change in redshift is coherent with structure

• $f\sigma_8$ quantifies the rate of structure growth, using galaxies as test particles

• Gravitational growth index $\gamma$ tests gravity separately from expansion history

\[
\gamma = 0.55, \text{ GR}
\]

\[
\gamma \neq 0.55, \text{ major discovery!}
\]

BigBOSS measures $\gamma \pm 0.02$

\[
f(z)\sigma_8(z) \propto \Omega_m^{\gamma} \exp \left[ \int \Omega_m^{\gamma} d \log a \right]
\]
## BOSS v BigBOSS

<table>
<thead>
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<th></th>
<th>BOSS</th>
<th>BigBOSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope</td>
<td>SDSS 2.5m</td>
<td>KPNO 4m</td>
</tr>
<tr>
<td>Number of simultaneous spectra</td>
<td>1000 (by hand)</td>
<td>5000 (by robot)</td>
</tr>
<tr>
<td>Survey duration</td>
<td>2009-2014</td>
<td>2017-2022</td>
</tr>
<tr>
<td>Total number of galaxies</td>
<td>1.5 million</td>
<td>26 million</td>
</tr>
<tr>
<td>Area (sq. degrees)</td>
<td>10,000</td>
<td>14,000+</td>
</tr>
<tr>
<td>Distance precision from galaxy BAO</td>
<td>~1% in 2 redshift bins</td>
<td>~1% in 35 bins</td>
</tr>
<tr>
<td>Dark Energy Figure of Merit</td>
<td>30</td>
<td>690</td>
</tr>
<tr>
<td>Gravity Figure of Merit</td>
<td>-</td>
<td>2500</td>
</tr>
<tr>
<td>Sum of neutrino masses</td>
<td>-</td>
<td>$\sigma \sim 0.024\text{eV}$</td>
</tr>
</tbody>
</table>
BigBOSS Stage IV science reach

BigBOSS Figure-of-Merit achieves Stage IV

*Independently verified by WFIRST Science Definition Team calculations of DETF figures of merit*

Fig. reproduced from WFIRST Science Definition Team report

Ly-α Forest

- First technique used galaxy distribution, alternative...
- Lyman-α forest technique uses line-of-sight absorption from back-lit quasar (QSO)

Redshifted from 1216Å
Emission Line Galaxies (ELGs)

ELGs unique signature of [O II] doublet, detectable from $z=0$ to $z=1.6$

Well-studied, BigBOSS has taken data to prove these ELGs drive BigBOSS wavelength coverage, throughput, & resolution

[O II] doublet at 3726.032 + 3728.815 Ang
BigBOSS detects to $z=1.6$ at 9700 Ang
Target Selection

- BAO with spectroscopy requires that we know what objects to put fibers on.
- PTF & ZTF provide us with optical photometry at the (uniform) depths we need
- Easy survey, only needs 2-bands of relatively shallow observations
- Proven on real imaging data (PTF), and verified with VLT spectroscopy
- This demonstration was required by our review panels.

Current PTF sky coverage for BigBOSS
- ~ 5000 sq. deg with R-band depth
- ~ 1000 sq. deg with g-band depth
BigBOSS target selection is based on optical+NIR data from SDSS, PTF, and WISE

4 million Luminous Red Galaxies

18 million Emission Line Galaxies

2.5 million Quasars
Target Distribution

$10^5$ Targets/dz(0.1)

- ELG (18.6M)
- LRG (4.2M)
- QSO (2.4M)
- Ly-a (0.8M)
Simulation: Emission Line S/N vs redshift

- Simulated end-to-end performance
- Generate redshifts with line estimates for Ly$\alpha$, [OII], H$\beta$, [OIII], and H$\alpha$
- Fit emission line templates for each line and redshift
Fiber System

- 120 micron core fibers
- 40m fiber run, no connectors, no lenslets!
- Colinear input beam

Fiber Ferrules at Actuator

Fiber Support & Distribution

Cross Spider Cable

Cable Junction Box Connection

Main Cable(s)

Cable Declination Pivot

Cable Polar Pivot

Cable Suspension

Cable Junction Box Connectors

[Connection]

Slit Assemblies
Fiber Performance Testing

Evaluation & Performance Test

- Verify Science performance parameters
- Establish Instrument & Component Tolerance & Life
- Validate components & simulations
- Establish manufacturers’ test methods

<table>
<thead>
<tr>
<th>System</th>
<th>Element</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber</td>
<td>Ferrule, Slit &amp; Connection</td>
<td>FRD collimated &amp; FRD converging</td>
</tr>
<tr>
<td>Fiber</td>
<td>Ferrule, Slit &amp; Connection</td>
<td>Near field converging</td>
</tr>
<tr>
<td>Fiber</td>
<td>Ferrule, Slit &amp; Connection</td>
<td>Transmission</td>
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<tr>
<td>Fiber</td>
<td>Front end, Gel</td>
<td>Transmission life</td>
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<tr>
<td>Fiber &amp; Spectrograph</td>
<td>Ferrule, Slit &amp; Connection Grating, Dichroic</td>
<td>AR coating throughput</td>
</tr>
<tr>
<td>Spectrograph</td>
<td>Grating</td>
<td>Efficiency</td>
</tr>
<tr>
<td>Spectrograph</td>
<td>Grating</td>
<td>Scatter: Near &amp; Far Field</td>
</tr>
<tr>
<td>Spectrograph</td>
<td>Dichroic</td>
<td>Efficiency, Wavefront</td>
</tr>
</tbody>
</table>

Measured 1.2° Injection Angle Tolerance for 90% EE from FRD

In f/# out

EE Encircled Energy in f/# out

Efficiency Convg. FRD
Near Field

Coll FRD

Illumination, 625nm LED
BOSS → BigBOSS Computing

- BOSS computing platform, exceptionally valuable
- Current test bed for spectral extraction for BigBOSS
- R&D underway on BOSS data
- Provides science requirements for BigBOSS performance
  — Eg. spectrograph issues can be studied and answered here.
Blanco provides open access for more than 200 nights/year of U.S. community access to Southern skies with a moderate-sized telescope (HP--A). … The COSMOS spectrograph offers increased efficiency for workhorse moderate-resolution optical spectroscopy in the South, and will provide spectroscopic follow-up of LSST sources. The Mayall and Blanco telescopes are uniquely well-suited among all the world’s 4m-class telescopes to providing high-multiplex wide-field optical spectroscopy (TC--O). DESpec and BigBOSS have proposed such instruments to be built with DOE contributions, although the wide-field spectrograph and DECam cannot be operated on the Blanco at the same time. [p95]

While we recommend ending operation of the Mayall as a user facility, this would not preclude its operation as a dedicated survey facility with funds from the competed MSIP and/or outside agencies. [p133]
First results from Reid et al (2012)

BOSS First Results on Redshift Space Distortions
Dark energy vs. gravity tested at $z=0.57$

Correlation functions would be circular if no gravitational growth

BOSS galaxies at $z=0.57$
BigBOSS science reach: BAO

Dark energy from Stage IV BAO
—Geometric probe with 0.3-1% precision from \( z=0.5 \rightarrow 3 \)

BigBOSS BAO “Hubble diagram”
Kitt Peak is a great site

Excellent seeing from Kitt Peak
Current weather statistics 72% useable nights

Mayall seeing measured from 17,268 MOSAIC images in NOAO Science Archive (Dey & Valdes 2012)

- Additional measurements of temperature-dependent seeing effects, points to improvements for Mayall