The Big Baryon Oscillation Spectroscopic Survey (BigBOSS)

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On behalf of the BigBOSS Collaboration
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The Nature of Dark Energy

- UCLA DM 1998 first report of accelerating universe (SCP and High-z)
- $\Omega_\Lambda = 0.72$, $\Omega_M = 0.28$ (82% CDM) Confirmed by CMBR, LSS
- Cosmological constant $\Lambda$? Evolving scalar field? $w = P/\rho < 0$ Deviation from GR?..
- After 14 years, no satisfactory theoretical explanation has emerged.
- Dark Energy Task Force (2006) has charted the path forward.

Study evolution of $w$: $w(z)=w_0 + w_a(1-a)$

- Multiple Techniques:
  I. Baryon Acoustic Oscillations (BAO) – geometry
  II. Clusters - NL gravitational growth
  III. Supernovae - geometry
  IV. Weak Lensing (WL) – geometry + NL gravitational growth

- New technique:
  V. Redshift Space Distortions (RSD) demonstrated (2008-2011) – L & NL gravitational growth

- Defines Figure of Merit (FoM) as “reciprocal of the area of the error ellipse enclosing the 95% CL in the $w$-$w_a$ plane.”

Progressive program to improve FoM

- Stage I (2006 knowledge)
- Stage II (existing experiments) (~50)
- Stage III (near term experiments 3x better than Stage II)
- Stage IV (10x better than Stage II)

BigBOSS will utilize both BAO (geometry only) and RSD (growth only) within the same data set to reach Stage IV for BAO with ground-based experiment.
The BigBOSS Collaboration

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

Non-U.S. Groups:
Ewha Womans University, Korea
French Participation Group
  APC, IAP- Paris; CPP, CPT, LAP
  Marseille; CEA, IRFU – Saclay
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
Baryon Acoustic Oscillations

Sound waves travel at $\approx c/\sqrt{3}$ until recombination. The sound horizon at recombination sets the $\approx 1^\circ$ characteristic angular scale of the CMB.

At the surface of last scattering ($z=1088$) this is a “standard ruler” used to establish the flatness of the universe. These $1/10^5$ level fluctuations grow into...

Map of Universe at 380,000 years (CMB)
Baryon Acoustic Oscillations

One wave

Many waves

... large scale fluctuations (150 Mpc co-moving) in the present galaxy distribution.

Map of galaxies today
Baryon Acoustic Oscillations

One wave

Many waves

... and can be seen as a peak in the power spectrum of the galaxy correlation function today.

Map of galaxies today
The power of spectroscopy

Full power of BAO only possible with spectroscopic surveys
  • Imaging-only surveys smear signal on same scale as BAO
  • FoM reduced $> 5x$

Imaging-only (photo-z) survey 5 bands

Spectroscopic survey

BAO scale

Benitez et al.
BigBOSS

- BAO measures two standard rulers
  - angular diameter distance $D_A(z)$
  - line-of-sight (Hubble constant $H(z)$)
- Both are sub-percent measures that improve with $z \sim \sqrt{V}$
Redshift Space Distortions

- **Measures gravitational growth**
  - linear growth (large-scale squashing)
  - non-linear growth (galaxy clusters)
- **Demonstrated with**
  - VVDS survey (Guzzo *et al* 2008)
  - WiggleZ survey (Blake *et al* 2011)
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BOSS - A Stage III Pathfinder for BigBOSS

- SDSS III experiment - 1000 fibers re-map focal plane to spectrographs.
- 1000 spectra/redshifts per observation
- 1.5 million galaxies $0.15 < z < 0.7$
- 160,000 QSOs $2.1 < z < 3.5$
- Definitive BAO $z < 0.7$ by 2014
- Pathfinder $z > 2$ using H-absorption to QSOs
- Plug plates do not scale to > 0.5 million objects/year
- Not possible to observe #s or volume required for Stage IV
BigBOSS on the Mayall at KPNO

Selected for “Large Science Programs Providing New Observing Capabilities for the Mayall 4m Telescope on Kitt Peak.”

500 hours in 5 years (2016 – 2020)
Survey area 14,000 sq deg
Precision redshifts $\sigma_z < 0.001(1+z)$ of over 20 million galaxies
(LRGs $0.5 < z < 1$ & ELGs $0.5 < z < 1.6$) to
  • Measure BAO feature
  • Trace matter power spectrum at small scales
  • Detect redshift space distortions
Constraints on early dark energy and curvature
  • Ly-\(\alpha\) forest in the spectra of > 600,000 quasars with $2.2 < z < 3.5$
  • Tracer QSOs $0.5 < z < 3.5$

5000 robotic fiber positioners on 1-m focal plane, f/4.5
Corrector lenses 3° FOV

http://bigboss.lbl.gov
Optical Corrector

- Magnifies f/2.1 Mayall prime focus to f/4.5 (17.1m EFL)
- 3° FoV
- Two prism based broadband atmospheric dispersion compensators (up to 60° from zenith)
- Geometric blur < 0.5 arcsec FWHM places < 70 μm FWHM spot onto 120 μm fiber over entire 1m focal plane.
Fiber Positioners

- 5000 12 mm fiber positioners mounted on curved 1m focal plane
- $\theta-\theta$, r-$\theta$ & flexure positioner prototypes exist (various options under study)
Spectrographs

- 5000 fibers feed 10 spectrographs
- Three channels
  - Red (800-980 nm, R > 4000)
  - Visible (620-840 nm, R > 3000)
  - Blue (360-660 nm, R > 1500)
BigBOSS Science Reach

• Current high resolution galaxy maps are sparse and largely missing intermediate redshifts
BigBOSS Science Reach

- BigBOSS will enlarge redshift-space maps to 24 million
- 10X larger than SDSS + SDSS-II + BOSS
- Necessary for Stage IV dark energy from BAO, RSD

2.5 million QSOs
18 million ELGs
4 million LRGs

Courtesy Anze Slosar
BigBOSS Science Performance

- BAO distance scale error $\sigma_{R}/R$ to < 1% for $0.5 < z < 3.0$.
- Measure $H(z)$ to 1.5% up to $z = 2.5$.
- Constrain growth, $\sigma_{8}(z)$ $f(z)$ with < 2% relative error.
- Measure galaxy power spectrum to < 1% up to $z = 1.5$.

Additional Goals

- Inflation: constrain spectral index and its running to < 1%.
- Measure $\Sigma m_{\nu}$ with $\sigma$ < 0.024 eV.

![Graph showing BAO distance scale and growth constraints.](image)
BigBOSS Dark Energy FoM

- BigBOSS projections based on BAO + RSD
  - Improvements possible with more linear modes \( k_{\text{max}} = 0.30 \, h \text{Mpc}^{-1} \)
  - DETF Figures-of-Merit
  - Priors from Figure-of-Merit Science Working Group (FoMSWG)
  - BAO (Stage III) from HETDEX + WiggleZ
  - SN (Stage III) FoMSWG assumptions for Stage III SNe

<table>
<thead>
<tr>
<th>FoM</th>
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<tbody>
<tr>
<td>BigBOSS ( k_{\text{max}} = 0.15 , h \text{Mpc}^{-1} )</td>
<td>430</td>
</tr>
<tr>
<td>+ BAO (Stage III)</td>
<td>437</td>
</tr>
<tr>
<td>+ SN (Stage III)</td>
<td>466</td>
</tr>
<tr>
<td>BigBOSS ( k_{\text{max}} = 0.30 , h \text{Mpc}^{-1} )</td>
<td>661</td>
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<td>691</td>
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BigBOSS (BAO + RSD) + LSST (WL)

- FoM better than space!
  - Independently verified by WFIRST Science Definition Team calculations of DETF FoM

Fig. reproduced from WFIRST Science Definition Team report
Conclusions

• BigBOSS is a **ground-based** Stage IV DE experiment that focuses on BAO and RSD.
  – 20 million galaxies + 2.5 million QSOs
  – BAO: Geometry, 1% precision $0.5 < z < 1.6$, $z = 2-3$
  – RSD: Gravitational growth, 2% precision @ 5 redshifts
  – Neutrino masses at 0.024 eV
  – Inflation probe utilizing more modes than Planck
• **Better, Faster, Cheaper!**
  – BigBOSS is a ground-based experiment highly competitive with space experiments.
  – Results by 2020
  – $$ factor of > 30 below $$$$$ space experiments
• Science improved by overlap with imaging surveys (DES, LSST..)
• “Full sky” and complete overlap with LSST survey area in next decade possible by re-siting BigBOSS in southern hemisphere.
Extra Slides
Beyond BAO: Neutrino Mass

- Neutrino oscillation measures $\Delta m^2$ of neutrino masses.
- BigBOSS power spectrum from galaxy maps measures $\Sigma m_\nu$ to 0.024 eV
- May be sufficient to resolve hierarchy problem
Beyond BAO: Inflation

- BigBOSS will substantially improve our knowledge of the slope of the primordial spectrum.
  \[ P(k) \propto \left( \frac{k}{k_0} \right)^{n_s + \frac{1}{2} \alpha_s \ln(k/k_0)} \]
  - Combines with Planck
  - Significance will depend on the number of modes in BigBOSS \( (k_{\text{max}}) \)

- BigBOSS will have high sensitivity to non-Gaussianities in the early Universe.
  \[ \Phi = \phi + f_{NL} \left( \phi^2 - \left< \phi^2 \right> \right) + ... \]
  - Planck sensitivity \( f_{NL} = 5 \), BigBOSS \( f_{NL} = 3.9 \)
  - Bispectrum of BigBOSS may improve this further