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."

The DOE/HEP Dark Energy Science Program: Status and Opportunities

Andreas Albrecht, *University of California, Davis*; **Scott Dodelson,** *Fermi National Accelerator Laboratory and University of Chicago*; **Chris Hirata,** *California Institute of Technology*; *Michigan*; **Bhuvnesh Jain,** *University of Pennsylvania*; *Chicago*; **Steve Kuhlmann,** *Argonne National Laboratory*; *ty*; **Saul Perlmutter,** *Lawrence Berkeley National Laboratory and y*; **Aaron Rodman,** *SLAC National Accelerator Laboratory*; *National Laboratory*; **Chris Stubbs,** *Harvard University*; **hite,** *University of California, Berkeley*

10 August 2012

ded for the discovery of dark energy. DOE's leadership was critical tremendous impact on our understanding of fundamental physics. dramatic evidence of physics beyond the particle physics Standard the mass-energy content of the Universe. DOE's ongoing resulted in continued observational progress, and we can expect a e next few years.

status and the future opportunities for research into the nature of gy program in the Cosmic Frontiers area of the DOE Office of ge photometric project, the Large Synoptic Survey Telescope , will advance the study of weak-lensing dark-energy techniques to idely acknowledged that multiple techniques are critical to a successful program of dark energy probes. In this Report we identify several key opportunities that would allow the DOE dark-energy program to attain Stage IV levels for the required multiplicity of techniques. The opportunities we outline will deliver a vibrant program with a continuous stream of results as the next era of dark energy exploration unfolds. Specifically:

1) 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

… and growing!

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.

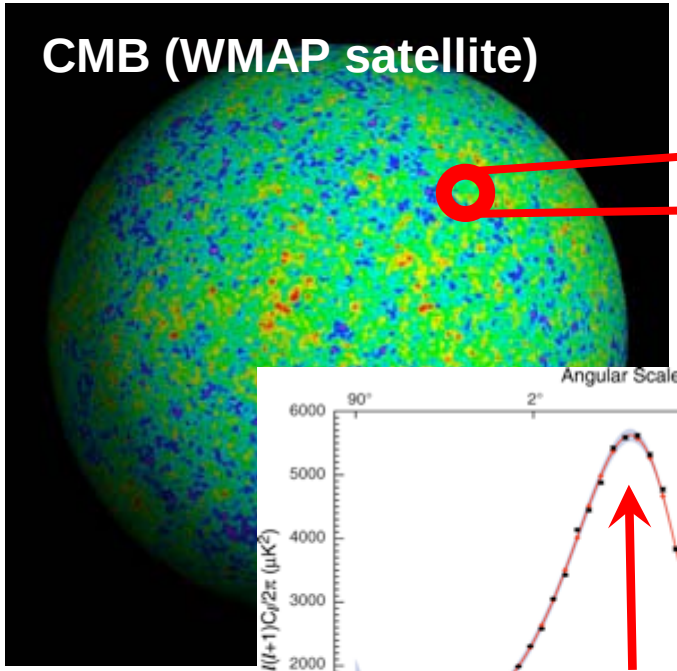
BigBOSS – Status

- **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.**

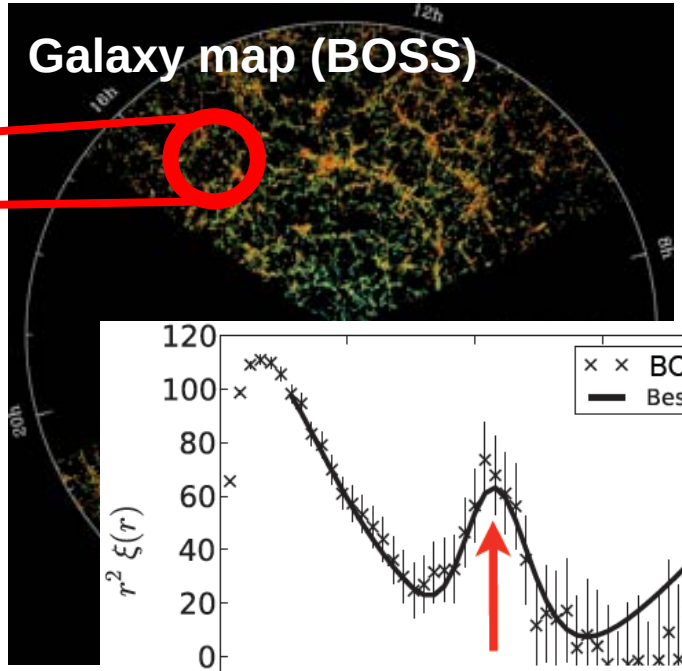
BAO

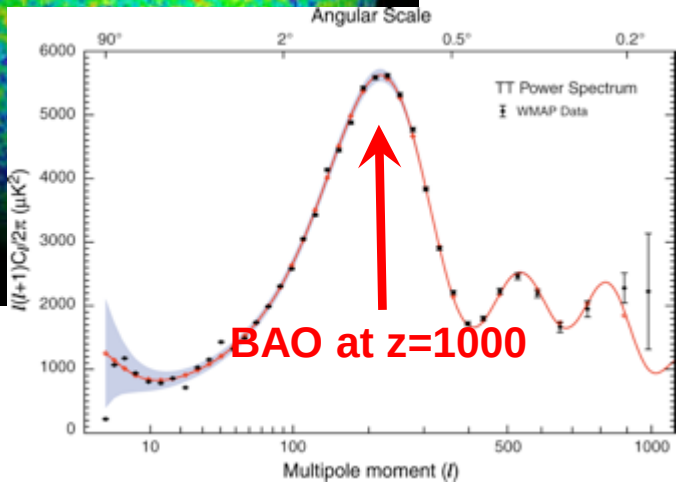
What are Baryon Acoustic Oscillations (BAO)?

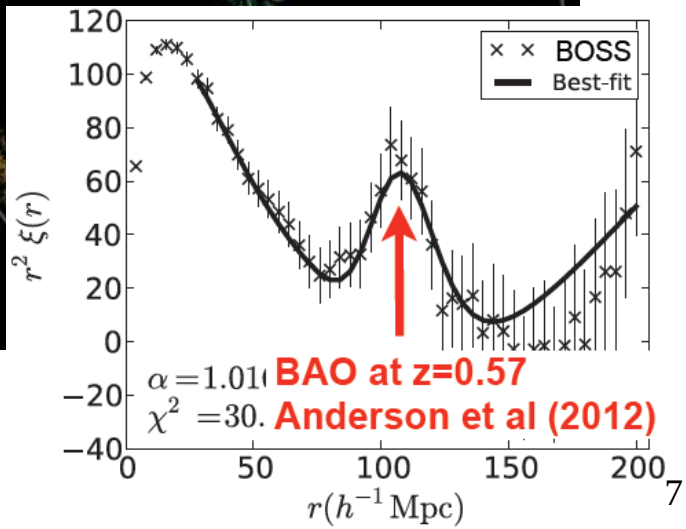
- The plasma of the early Universe supports sound waves
  - Speed of sound ~ c/√3
  - Sound wave stalls, leaving imprint on density fluctuations.
  - Characteristic scale of 153.2 Mpc ~ 4.7e24 m
  - Density fluctuations are amplified under gravity, sites for galaxies



BAO ruler

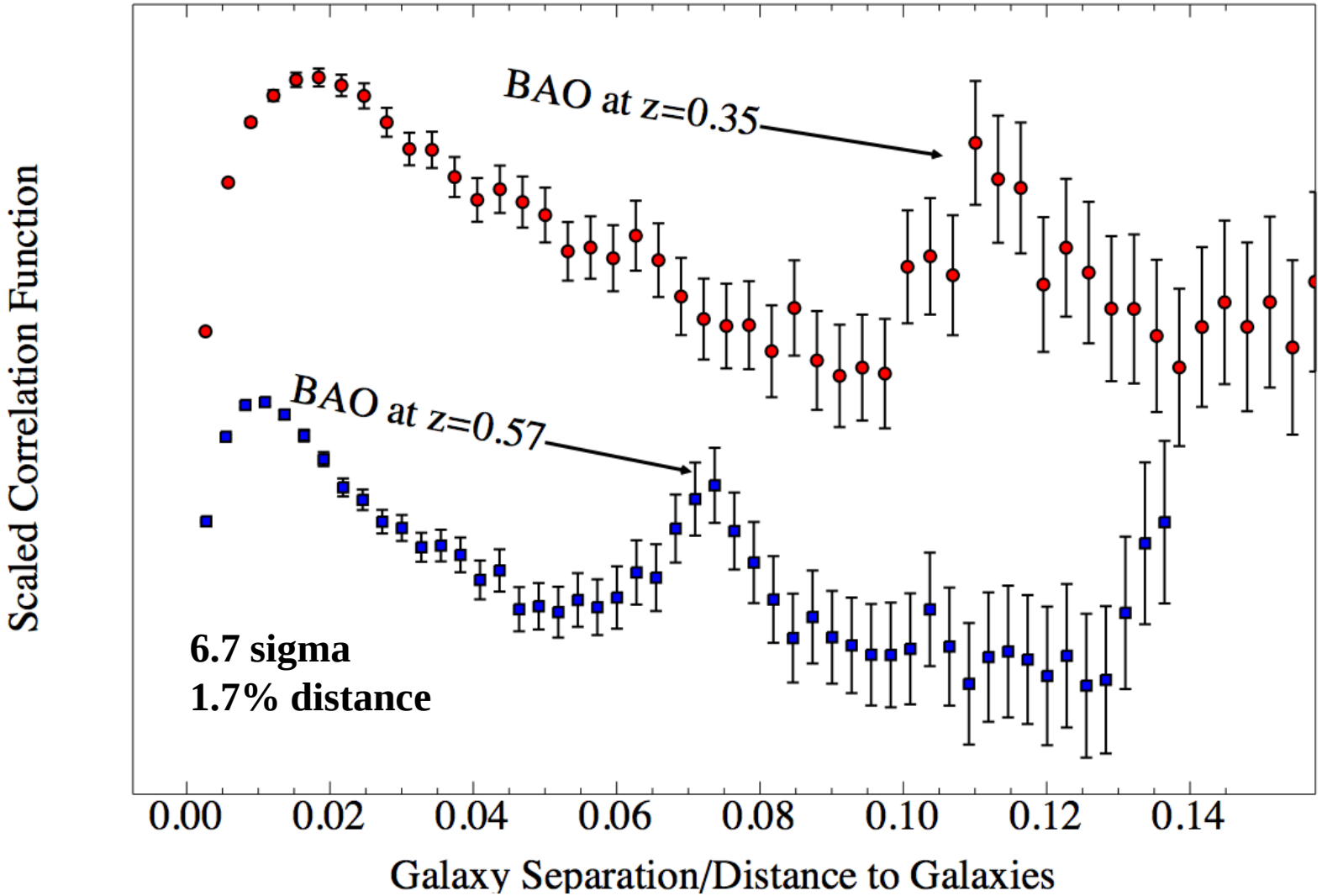




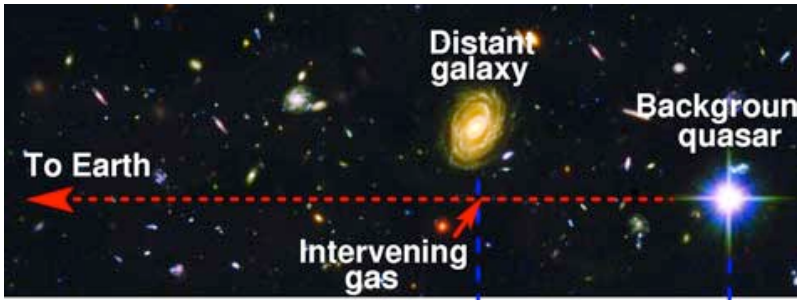


BOSS measures the BAO standard ruler using the distribution of galaxies

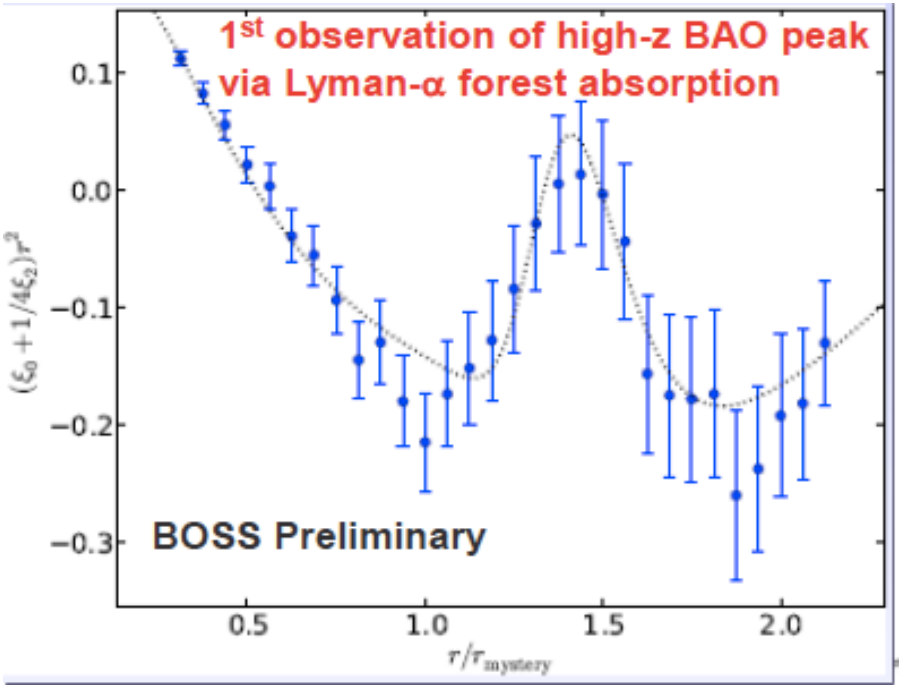
BOSS results with 1/3 of Data; on track for 1% distance measurements at 2 redshifts



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

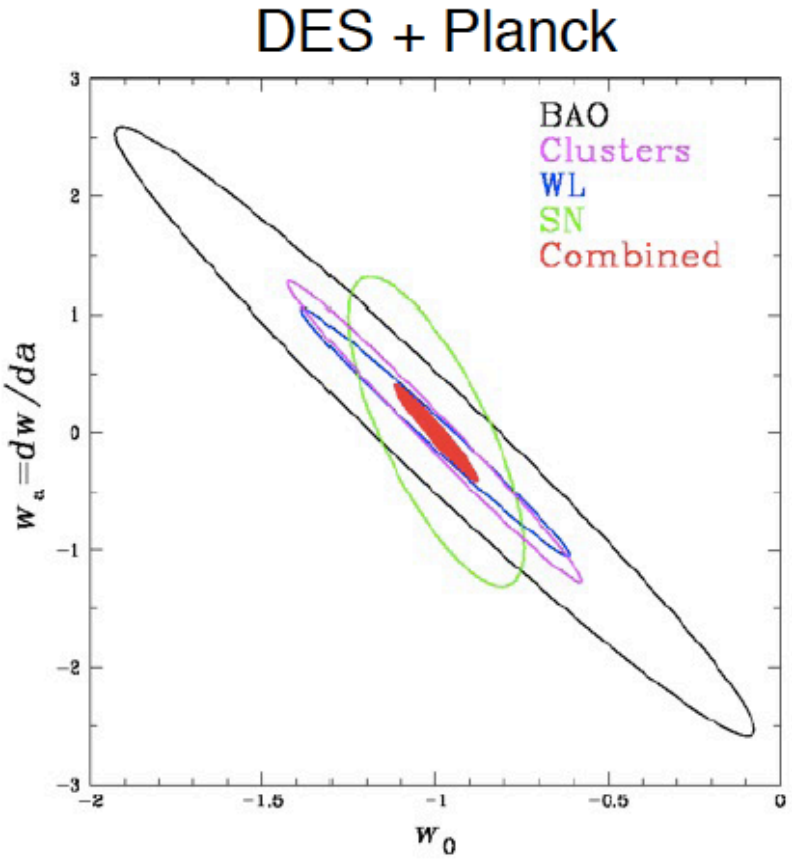
Lyman-α forest technique uses line-of-sight absorption from back-lit quasar (QSO)

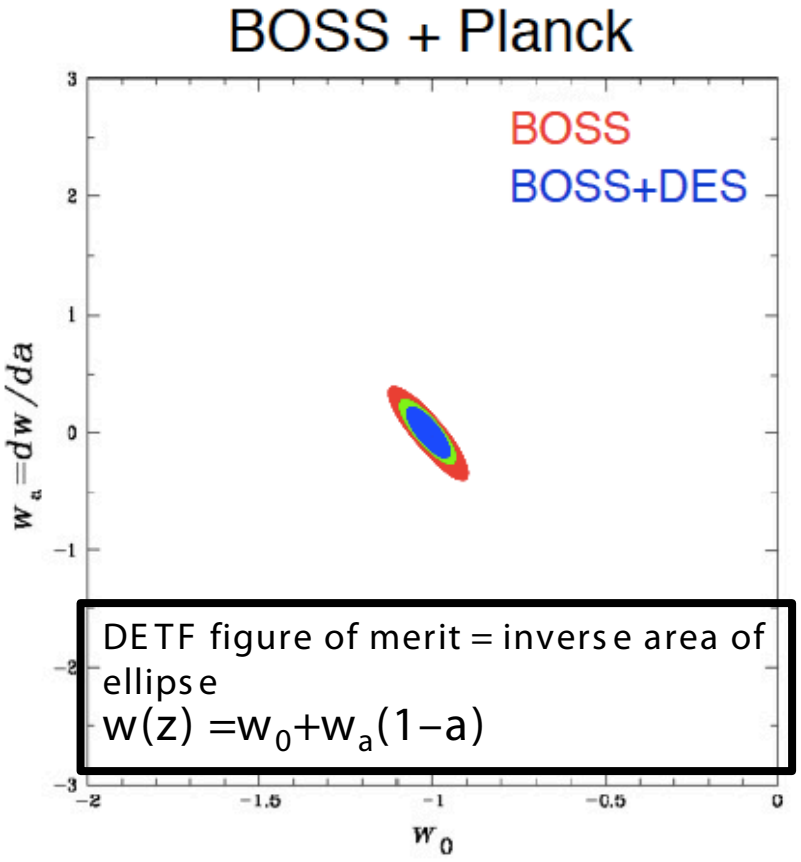
Will show that the Universe was decelerating before it accelerated!

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)

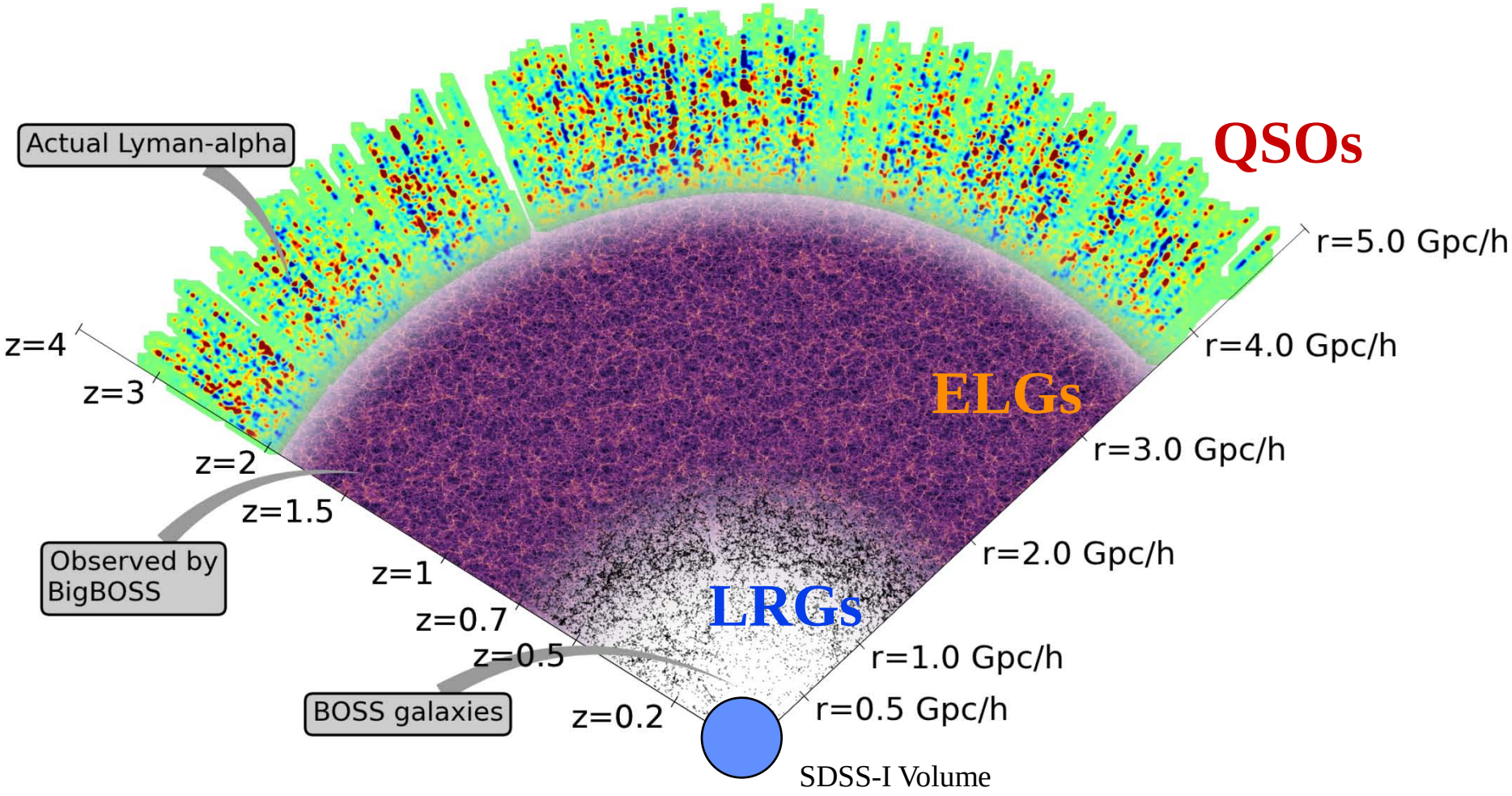
Does not include Lyman-alpha forest or redshift space distortion measurements.





Science Goals

BigBOSS is BIG

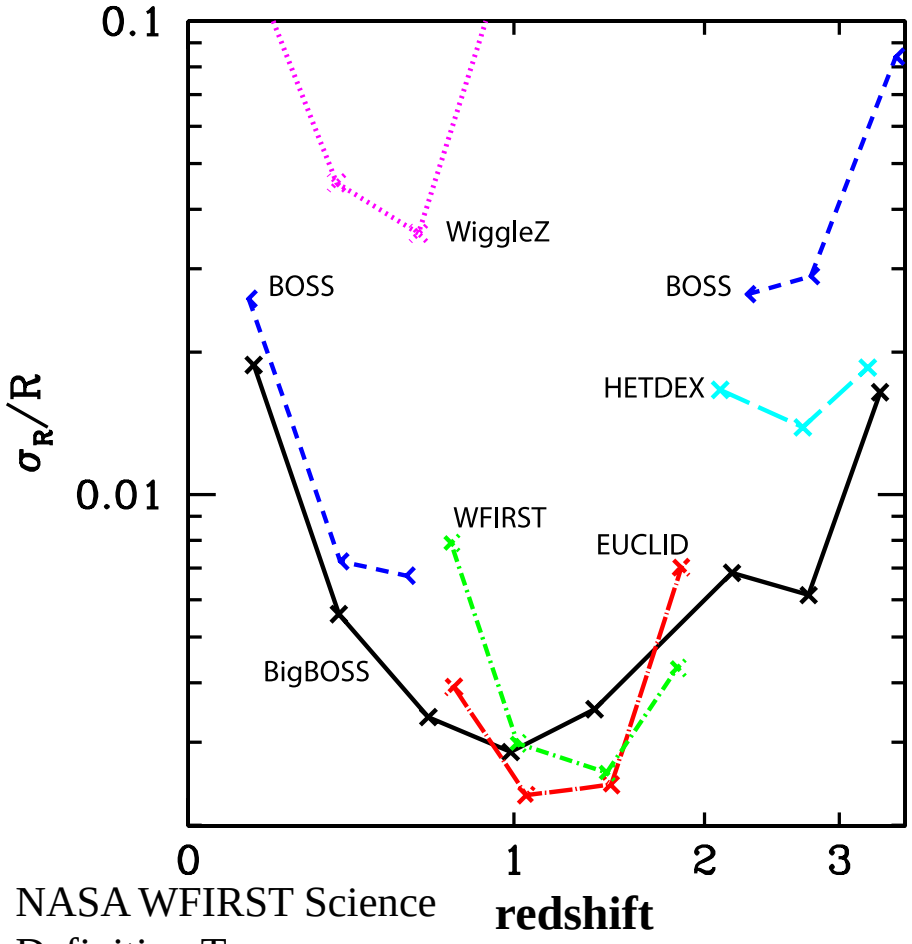


SDSS ~ $2h^{-3}Gpc^3$ → BOSS ~ $6h^{-3}Gpc^3$ → BigBOSS ~$50h^{-3}Gpc^3$

BigBOSS Science Goals

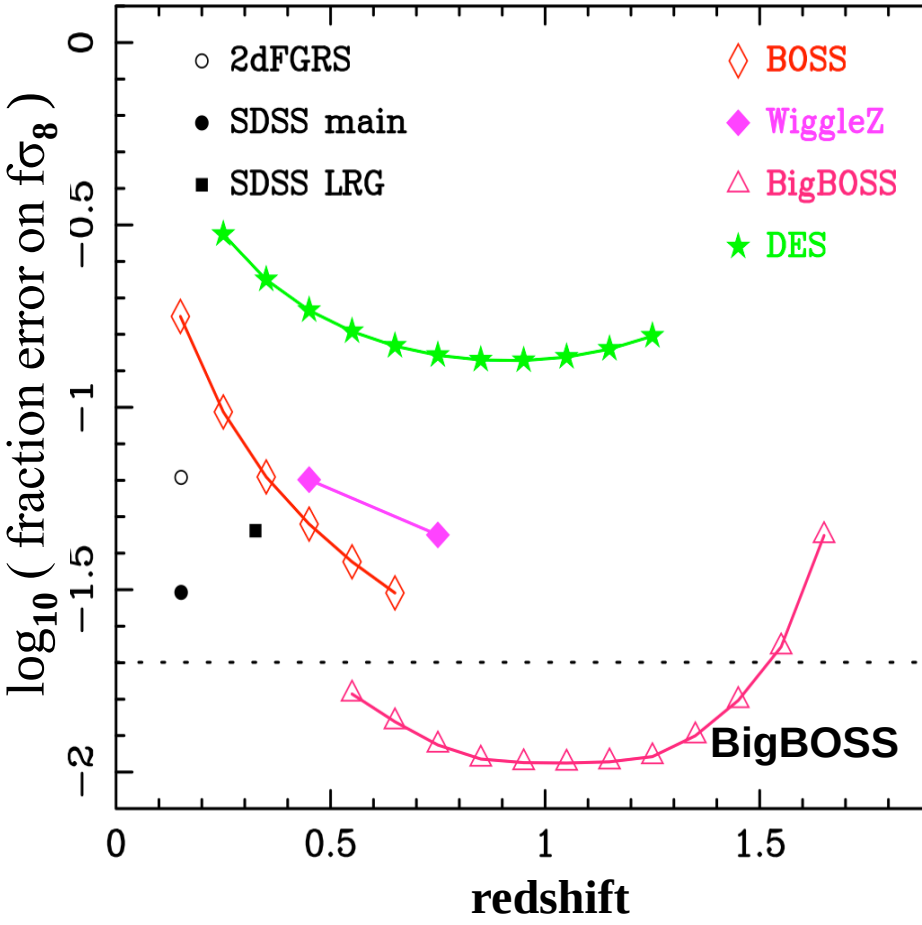
DETF Stage IV - Figure of Merit x10 over Stage-II

Sub-1% distance error



NASA WFIRST Science Definition Team

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



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

August 2012 – The Dark Energy Science Report aka Rocky-III

- **Recommends Stage IV BAO + RSD experiment in 2017-2022 timeframe**

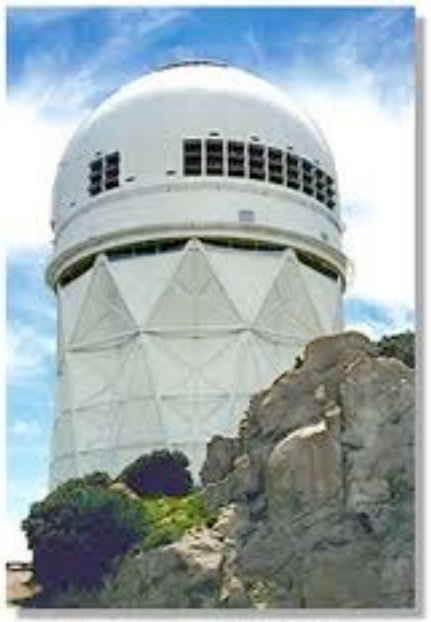
- **Must be ambitious in order to achieve Stage-IV**
  - **BigBOSS was designed to satisfy Stage-IV BAO**
  - **BAO Hubble Diagram up to redshift z~3.5**
  - **BOSS FOM = 30**
  - **BigBOSS FOM = 700, Gravity-FOM= 2500, $\sigma(\Sigma m_\nu)$ ~ 0.024eV**

- **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



Mayall 4-Meter Telescope

Investigated Siting Options

Name	Site	Notes and Exclusions	M1 f/#	M1 Diam. (m)	f/#	f (m)	Suitable for BigBOSS 3-degree corrector?
Vista	Chile	ESO	f/1.0	4.1	1	4.1	no
Starfire	New Mexico	Military	f/1.5	3.5	1.5	5.2	no
SOAR	Chile		f/1.7	4.2	1.7	7.1	no
WIYN	Arizona		f/1.8	3.5	1.8	6.3	no
ARC	New Mexico		f/1.8	3.5	1.8	6.3	no
Discovery Channel	Arizona		f/1.9	4.2	1.9	8.0	marginal, with 1.5m C1
Galileo TNG	Spain		f/2.2	3.6	2.2	7.9	marginal
NTT ESO	Chile	ESO	f/2.2	3.5	2.2	7.7	yes
William Herschel	Spain		f/2.5	4.2	2.5	10.5	marginal
UKIRT	**Mauna Kea**	**NIR**	**f/2.5**	**3.8**	**2.5**	**9.5**	**Under sized supports**
Victor Blanco	**Chile**	**Twin to Mayall**	**f/2.8**	**4**	**2.8**	**11.2**	**yes**
Mayall	**Arizona**	**Twin to Blanco**	**f/2.8**	**3.8**	**2.8**	**10.6**	**yes**
AEOS	Maui, Hawaii	Military	f/3.0	3.7	3	11.1	yes
ESO 3.6m	Chile	ESO Committed	f/3.0	3.6	3	10.8	yes
AAT	Australia	2 arcsec seeing	f/3.2	3.9	3.2	12.6	yes
Hale	Palomar		f/3.3	5.1	3.3	16.8	no, massive corrector
MPI-CAHA	Calar Alto, Spain		f/3.5	3.5	3.5	12.3	yes
CFHT	**Mauna Kea**	**Proposed 10m**	**f/3.8**	**3.6**	**3.8**	**13.7**	**yes**

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

BigBOSS tracers of dark energy

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)

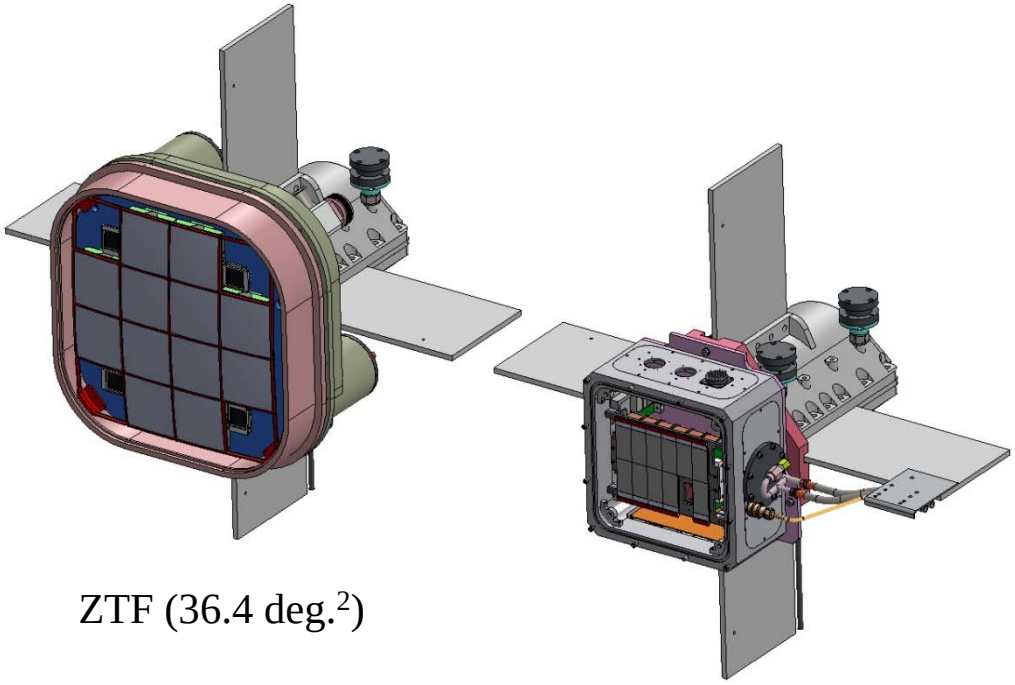
- *i*PTF (g-band data to 5,000 deg^2)

-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



ZTF (36.4 deg.^{2})

*i*PTF (7.2deg.^{2})

Telescope	AΩ
*i*PTF/PTF	8.7
DES	11.7
ZTF	46.5
LSST	82.2

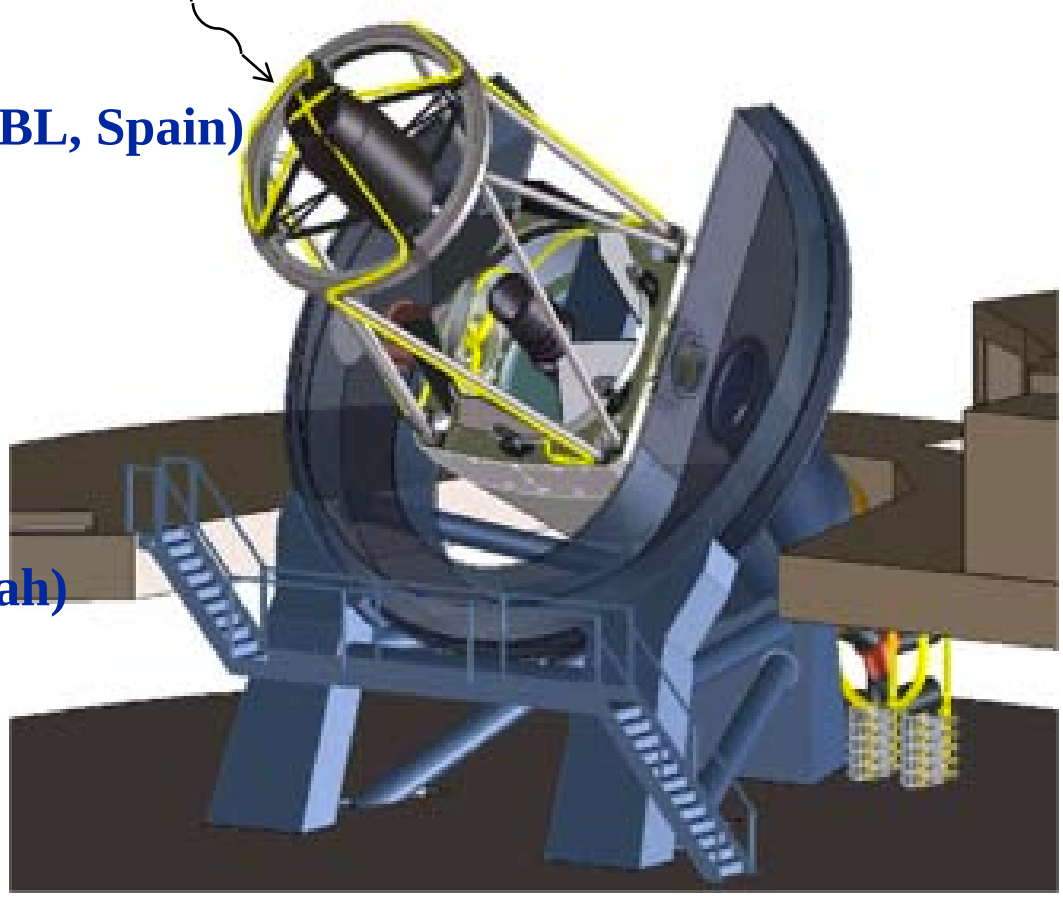
- Significant upgrade to the Palomar Oschin Schmidt focal plane
- ZTF can perform the BigBOSS LRG/ELG target selection in 2 filters in 1 year
- Project led by Caltech; chips already being fabricated (e2V)
- On-sky 2015, agreement to deliver data to BigBOSS

Technical Status

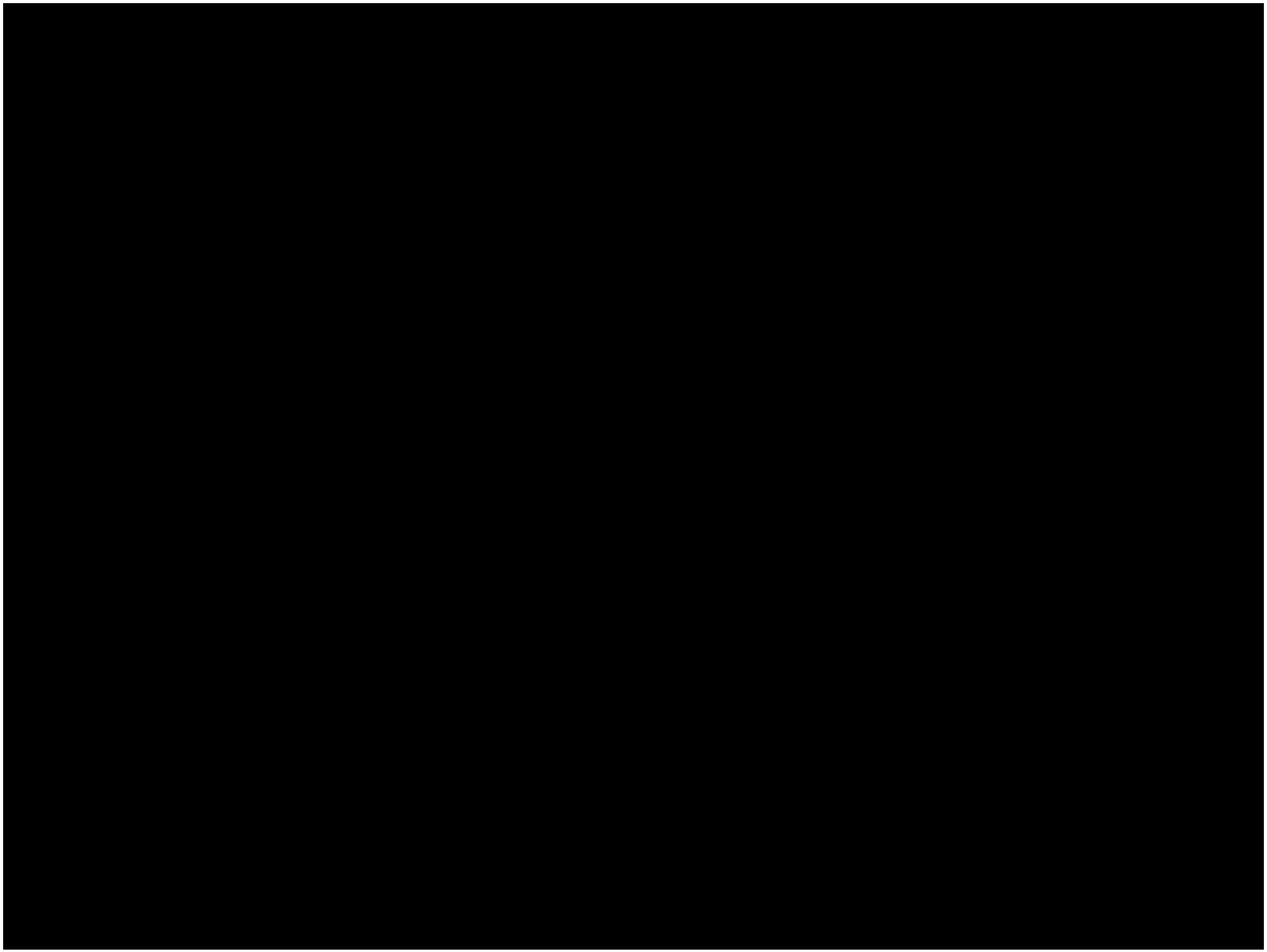
Instrument Overview

A photon's path through the BigBOSS instrument:

- **4m primary class telescope (KPNO)**
- **7º 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-α 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."

Department of Energy

Review Report

For the

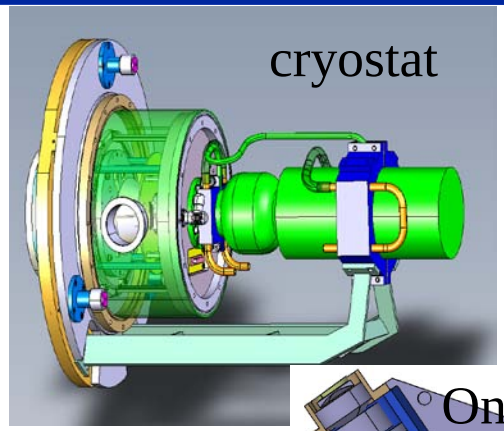
BigBOSS proposal

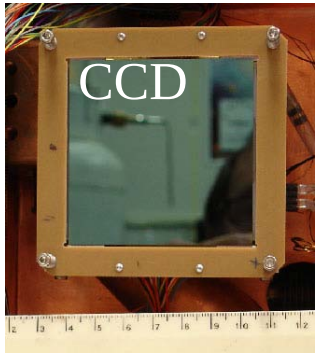
DECEMBER 2011

Spectrographs

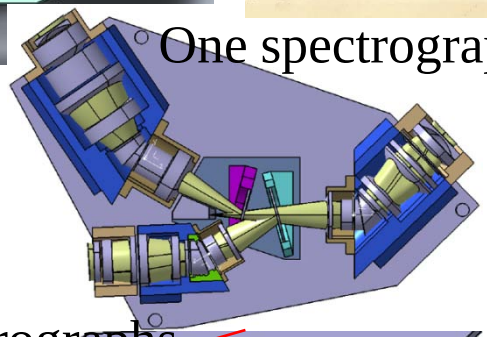
Spectrograph

- 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

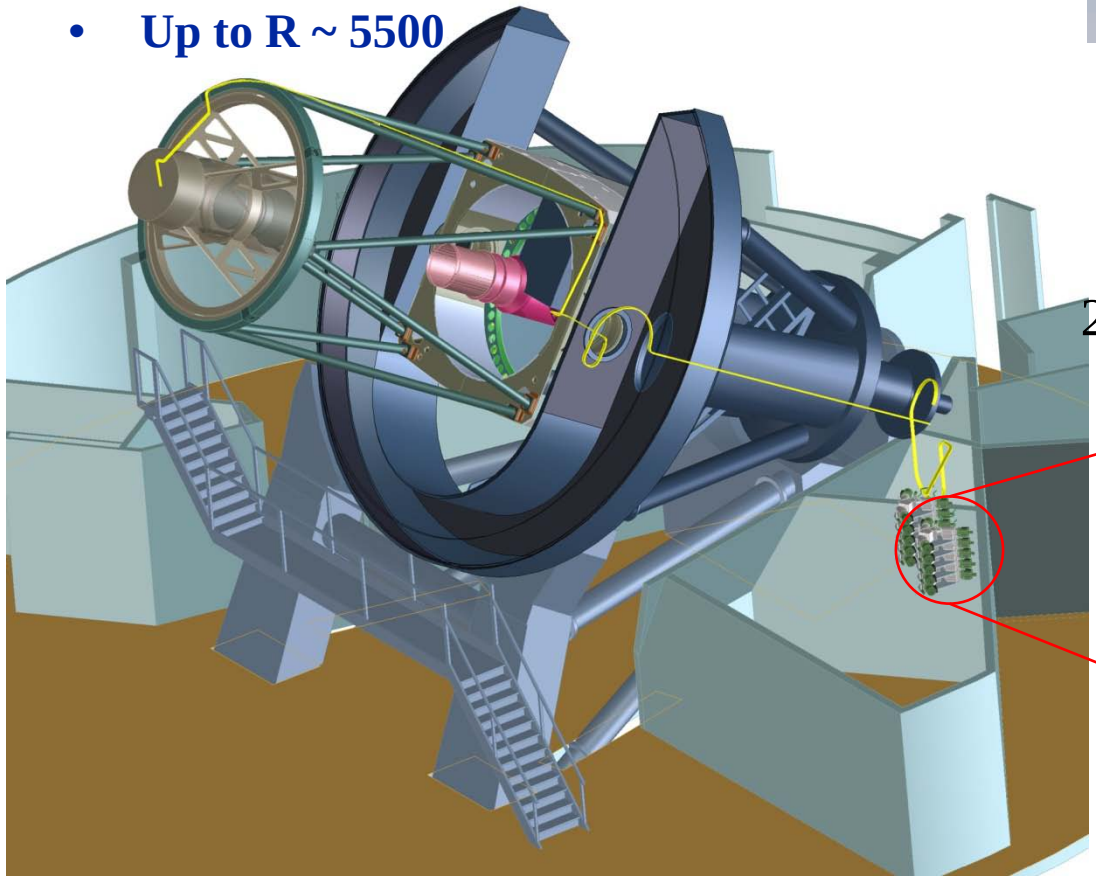


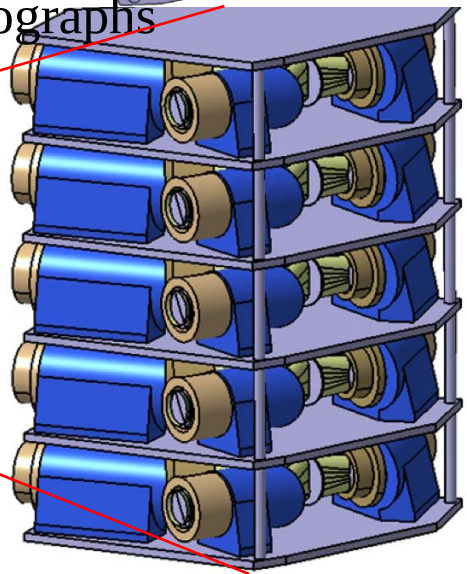


One spectrograph



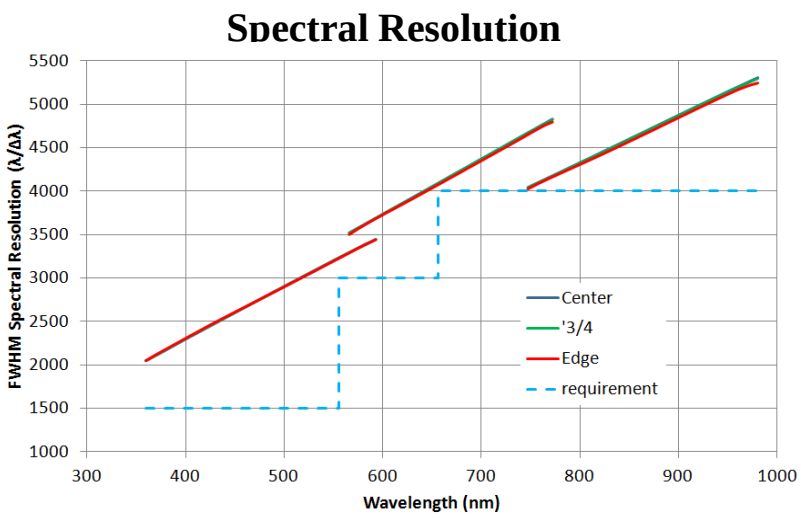
2xFive spectrographs

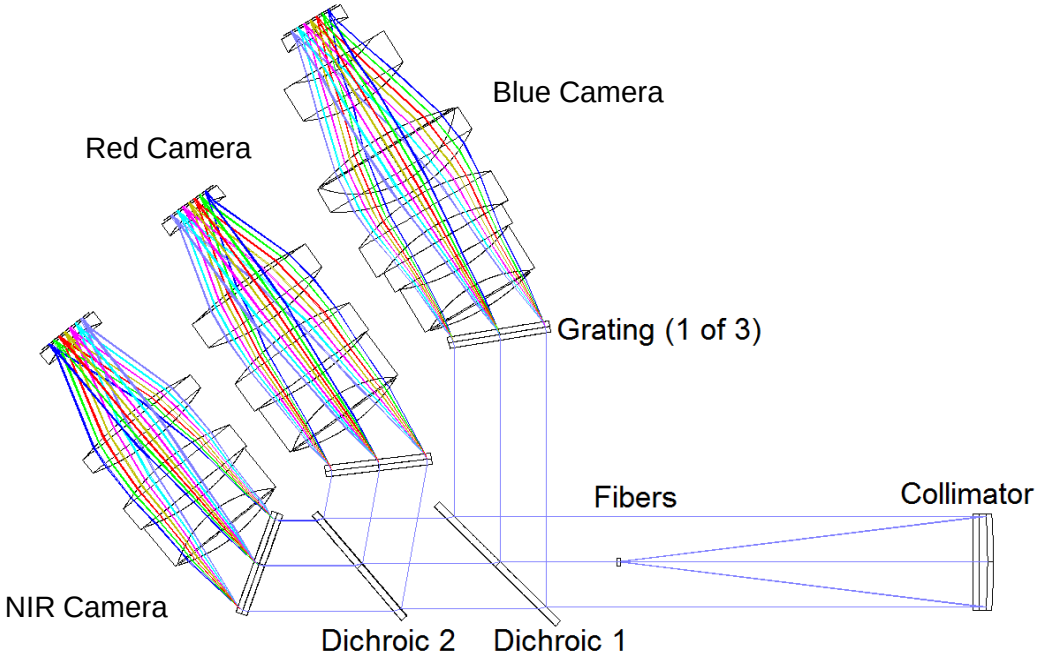


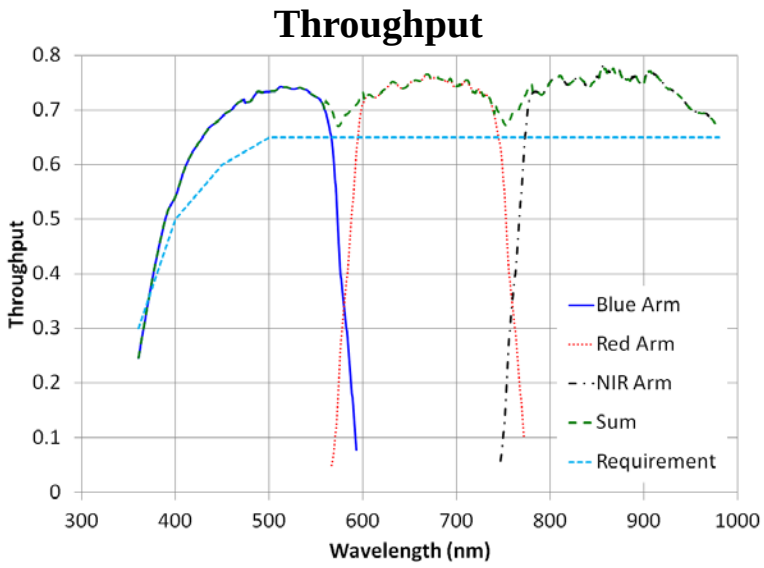


Spectrograph Properties

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

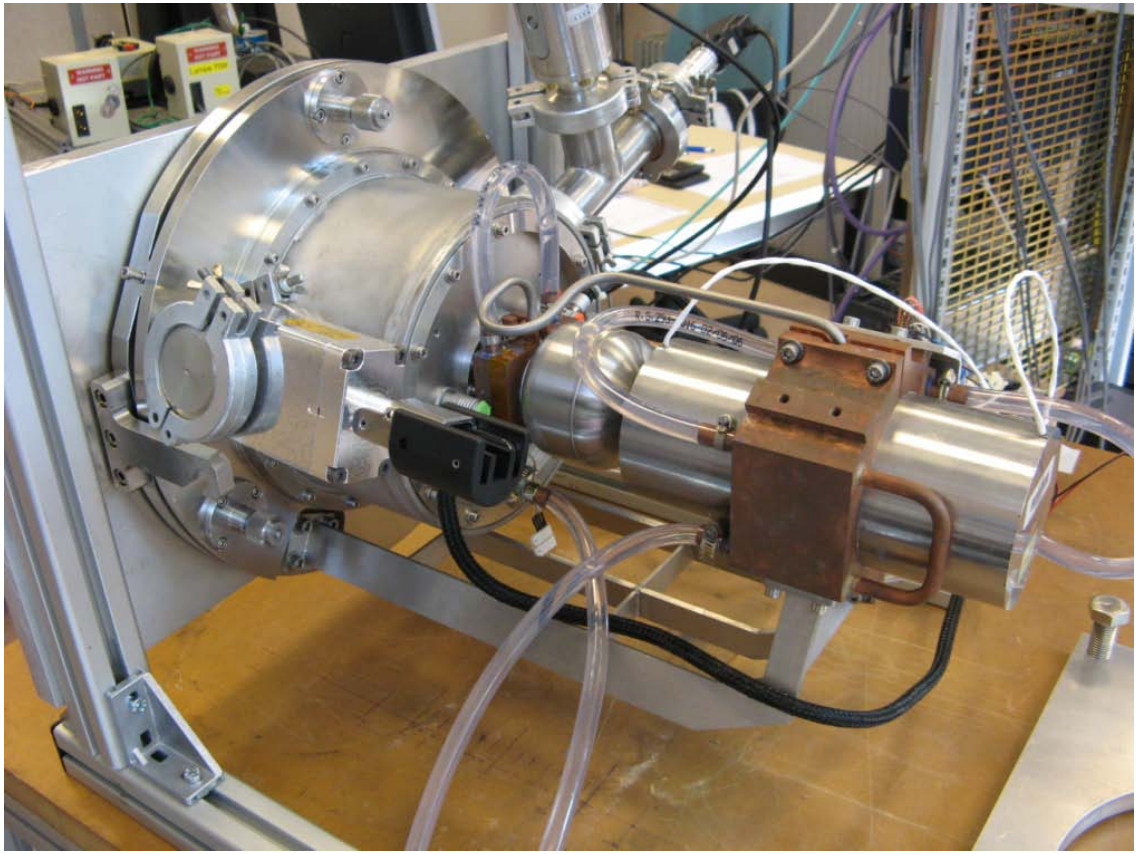






BigBOSS Cryostat (France)

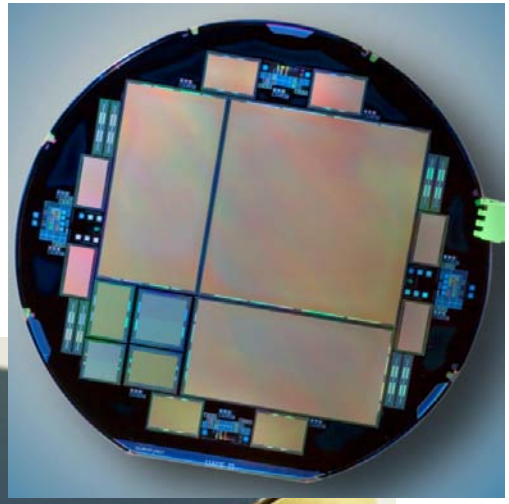
- ✓ CCD Temperature within +/-1K ; stability within 0.3K



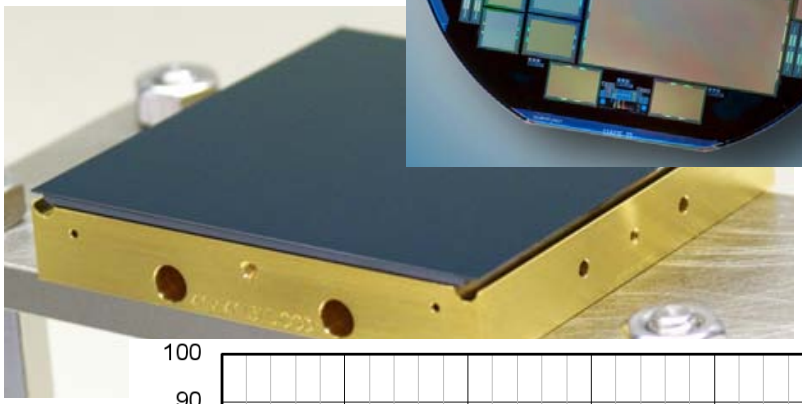
BigBOSS cryostat test Bench : vessel and cryocooler

CCD's

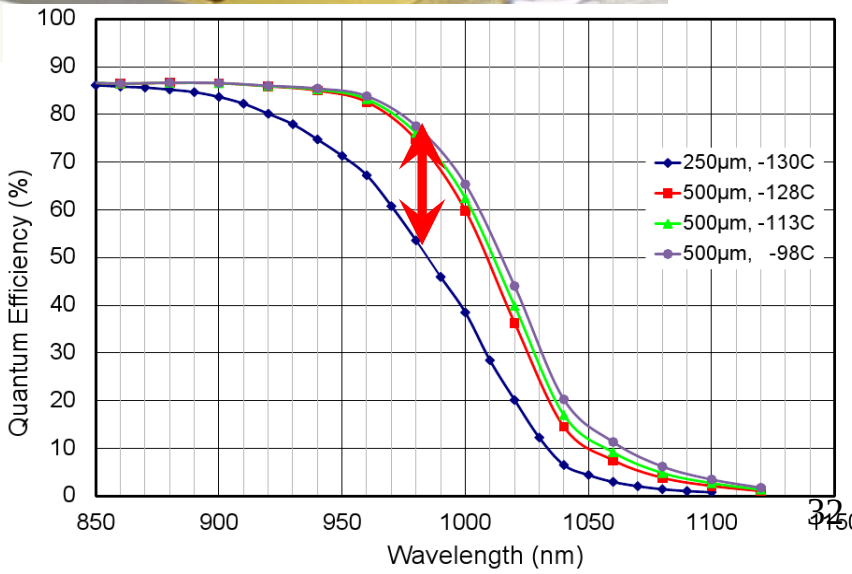
- **Using BOSS CCD design (low noise, high QE)**



- **Packaging effort at FNAL**
  - **SiDET**

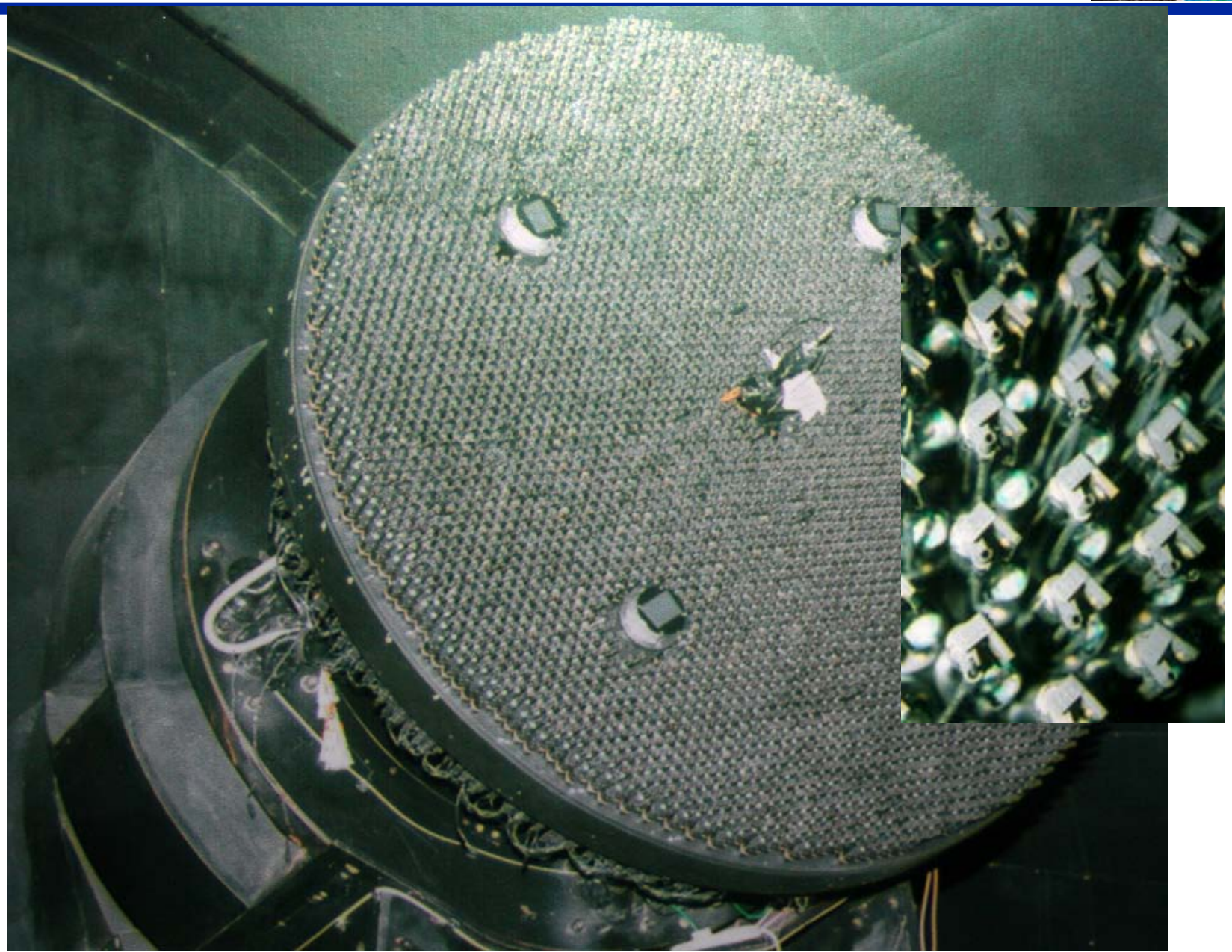


- **"super-red" sensitive**
- **Low charge diffusion variant**

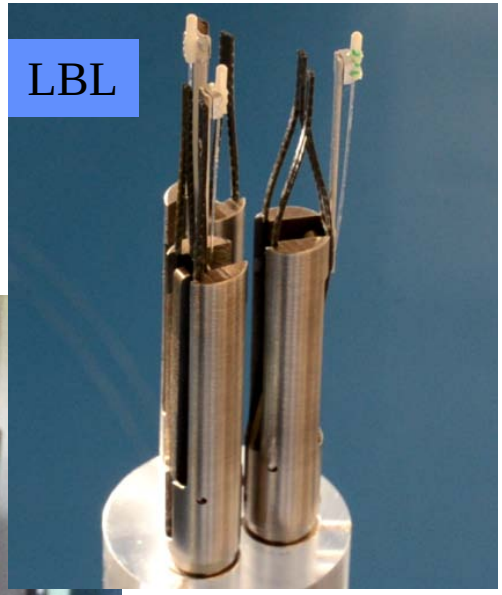


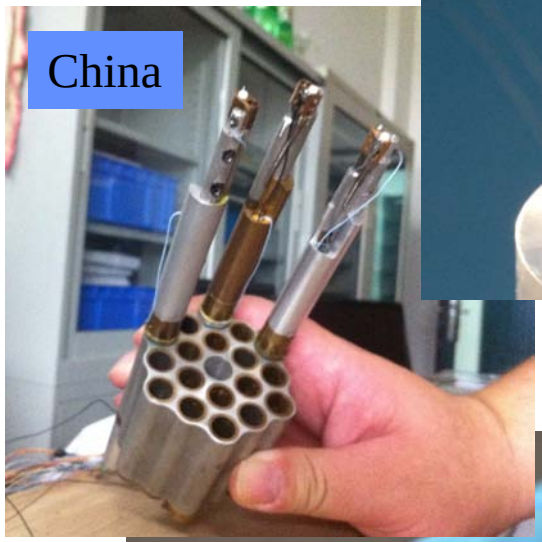
Fiber Positioners and Fiber System

LAMOST (China) Focal Plane
4000 actuators



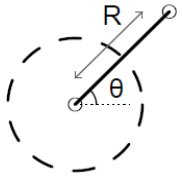
Fiber Positioners

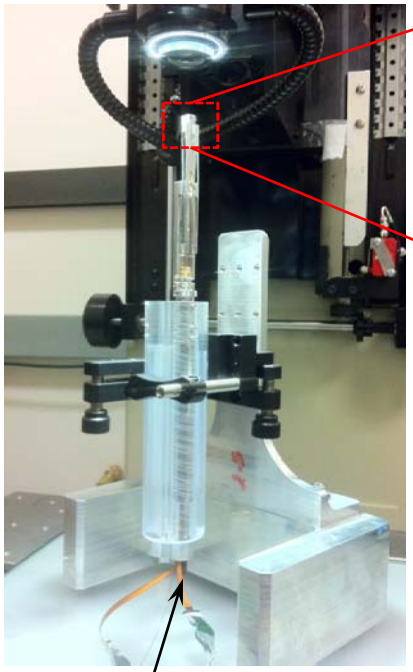




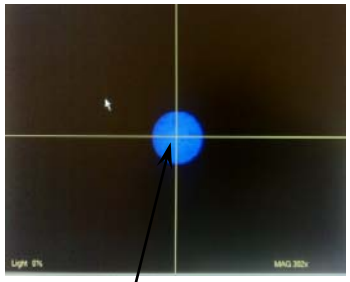
- **Results**

	R [μm]	θ [μm]
Absolute Accuracy	5.6	7.0
Repeatability	± 3.6	± 3.2
Step Size	1.0 ± 0.5	1.2 ± 0.6





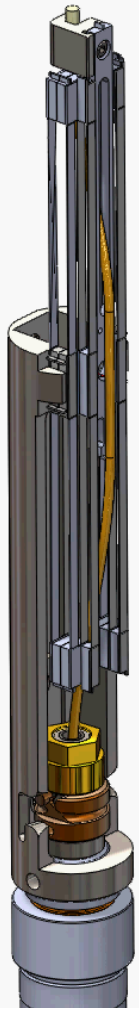
Fiber tip on actuator



L0mm Actuator

Fiber Backlit for Measurement

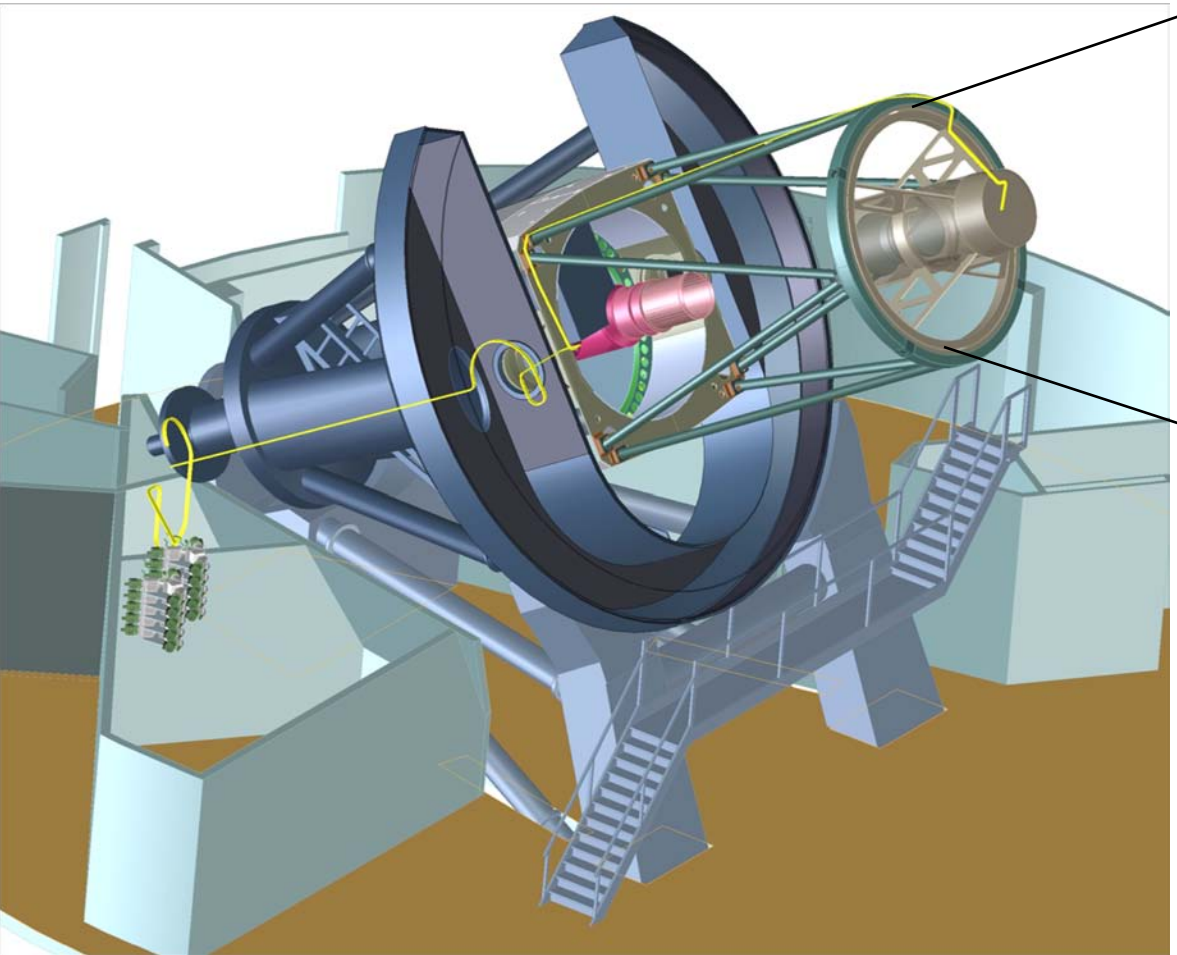
Fiber Positioning in BigBOSS

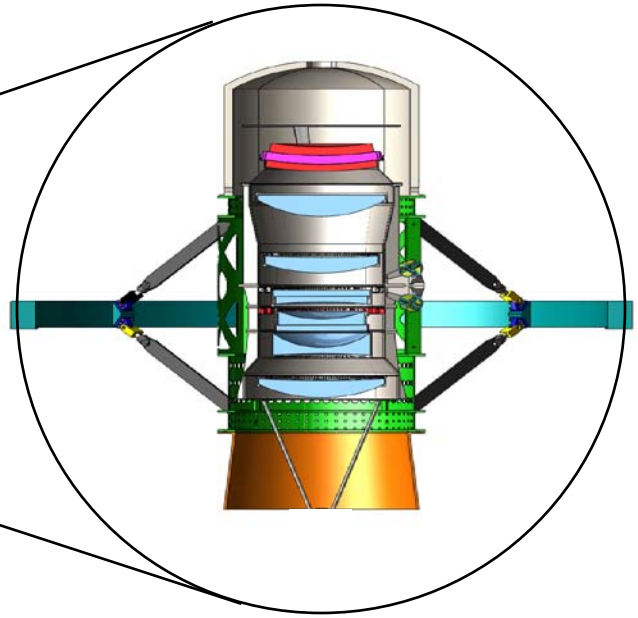


Corrector

New 7^0 deg^2 FOV Corrector

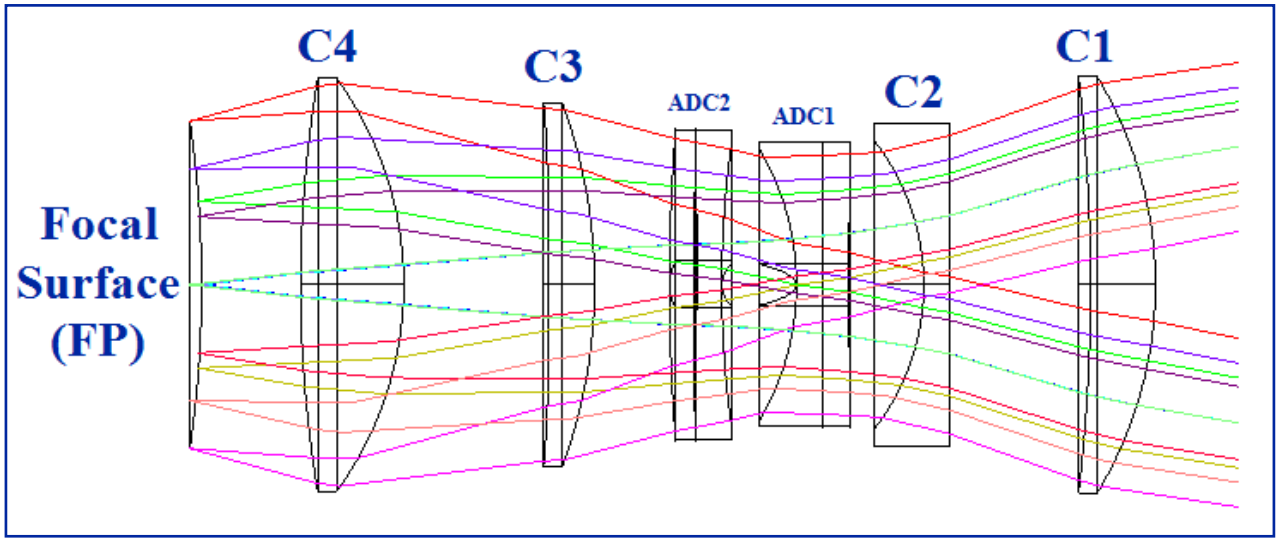
- New optical concept with ADC
  - Corrector ingests light at F/2.8, outputs at F/4.5



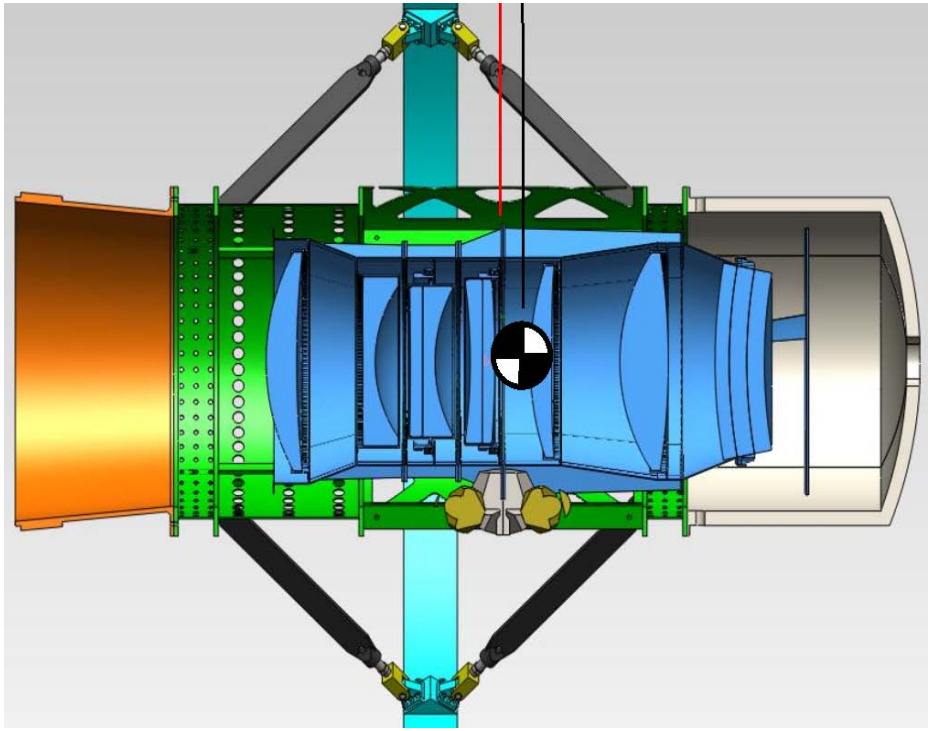


Widefield prime focus corrector

- 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



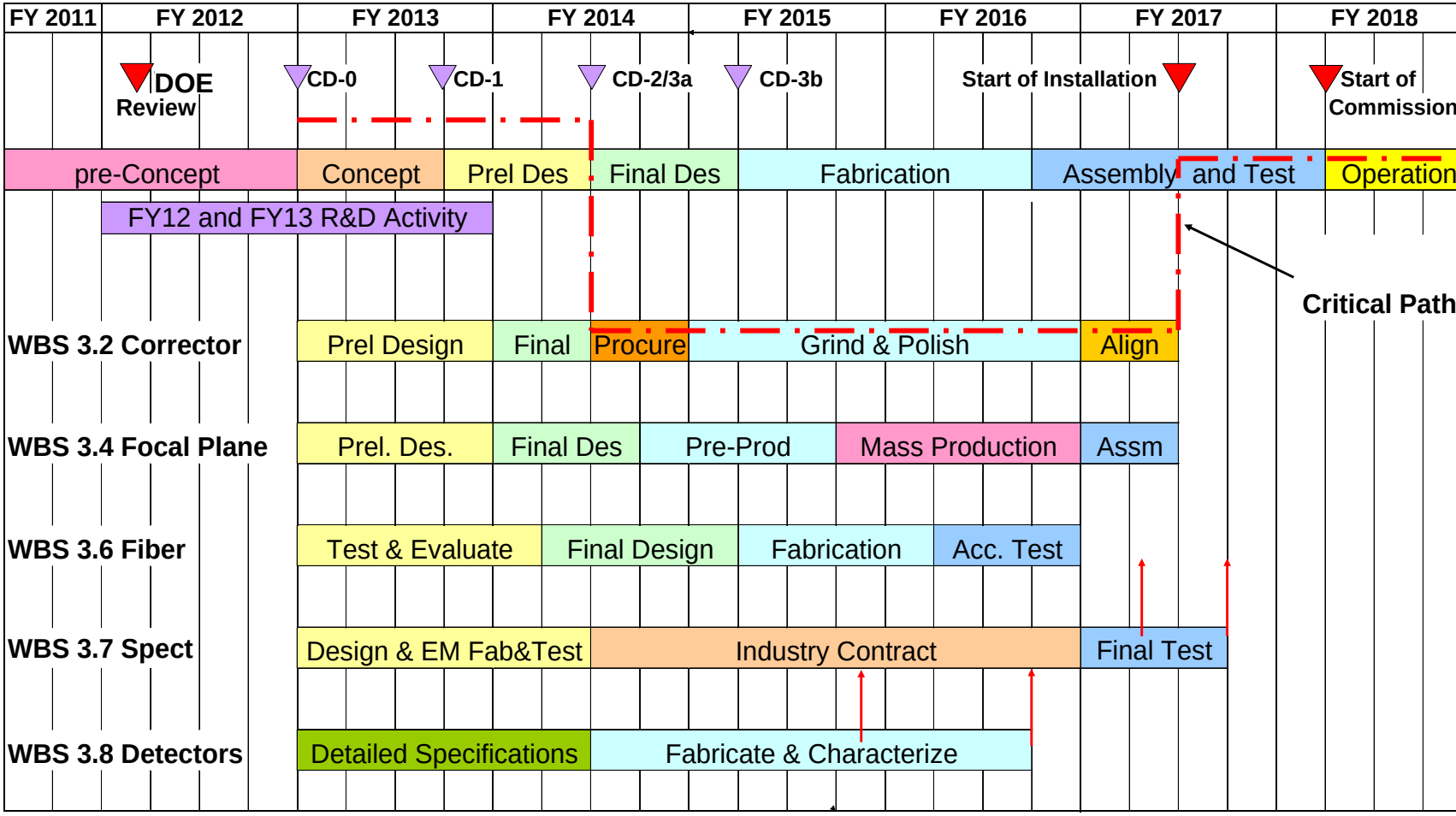
Corrector work at FNAL



- FNAL is doing a full FEA analysis of the corrector and hexapod configuration.
- Current design satisfies spec.

Simplified Schedule

R&D Started in 2009



Dedicated Surveys

Dedicated surveys get the job done! Good utilization of an expensive instrument.

Instrument	Telescope	Ref	Nights / year	No. Galaxies	sq deg	Ops Start
SDSS I+II	APO 2.5m	1	150	85K LRG	7600	1999
Wiggle-Z	AAT 3.9m	2	60	239K	1000	2007
BOSS	APO 2.5m	3	150	1.4M LRG + 160K Ly-α	10000	2009
HETDEX	HET 9.2m	4	60	1M	420	2014
BigBOSS	KPNO 3.8m	5	100	25M + 1M Ly-α	14000	2017
SUMIRE PFS	Subaru 8.2m	6	20	4M	1400	2018
4MOST	VISTA 4.1m	7	--	6-20M bright objects	15000	2019
DESpec	Blanco 4.0m	8	70	8M	5000	2020
EUCLID	1.2m space	9	365	52M	14700	2021

ref 1 Eisenstein et al AJ 122, 2267 (2001) & astro-ph/0501171 (2005); Hogg et al ApJ 624, 54 (2005); www.sdss.org/

2 Drinkwater et al MNRAS 401, 1429 (2010); Scrimgeour et al arXiv 1205.6812 (2012)

3 Eisenstein et al AJ 142, 72 (2011); Bolton et al arXiv 1207.7326 (2012); http://www.sdss3.org/dr9/

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

8 Abdalla et al arXiv 1209.2451 (2012)

9 Amiaux et al arXiv 1209.2228 (2012)

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

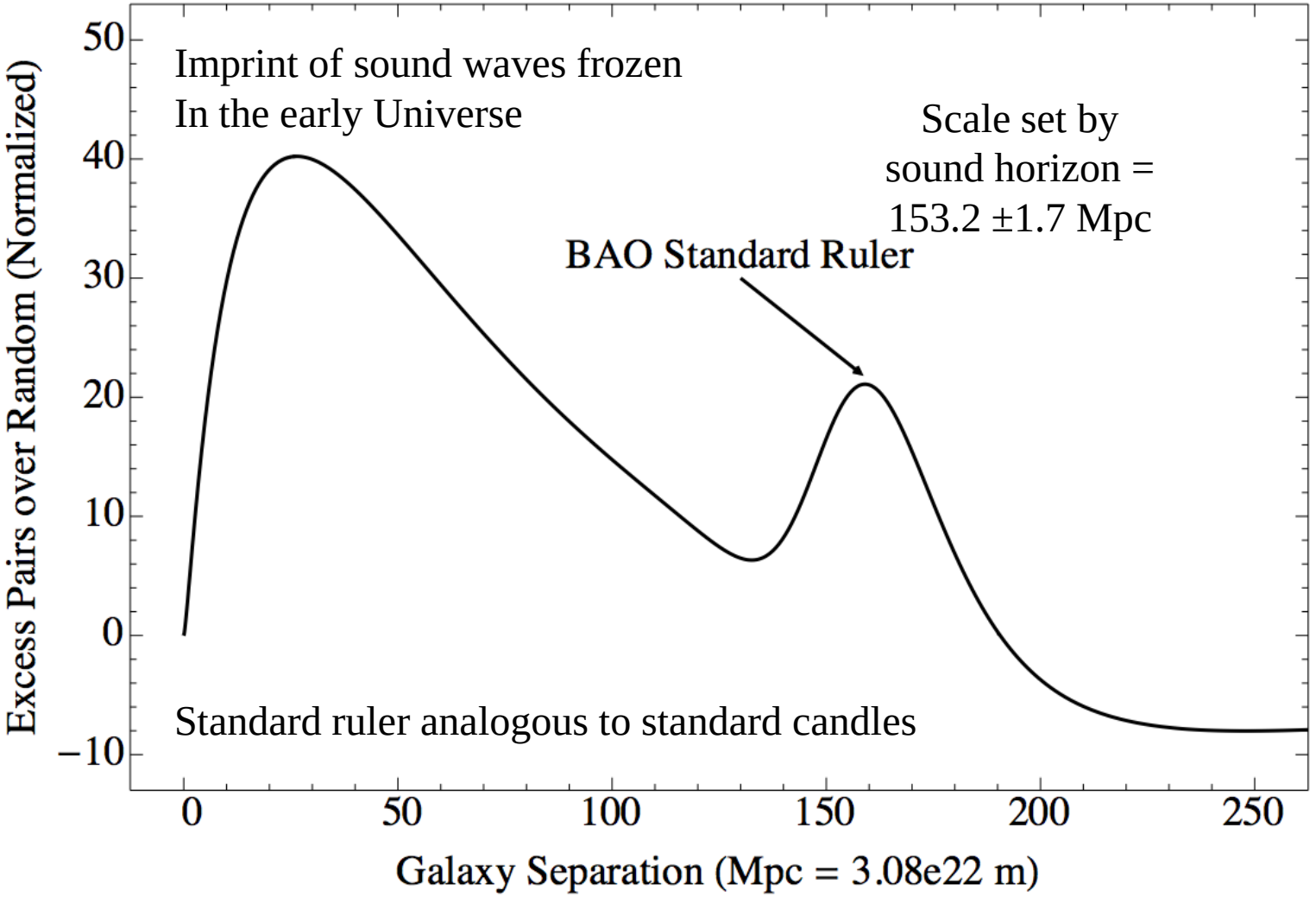
- **FNAL:**
  - **Critical role in BigBOSS, essential for project success!**
  - **Brings unique expertise on:**
    - **Corrector barrel and hexapod design & fabrication**
      - **FNAL effort led by Gaston Gutierrez**
    - **CCD packaging & testing (SiDET)**
      - **FNAL effort led by Juan Estrada**

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



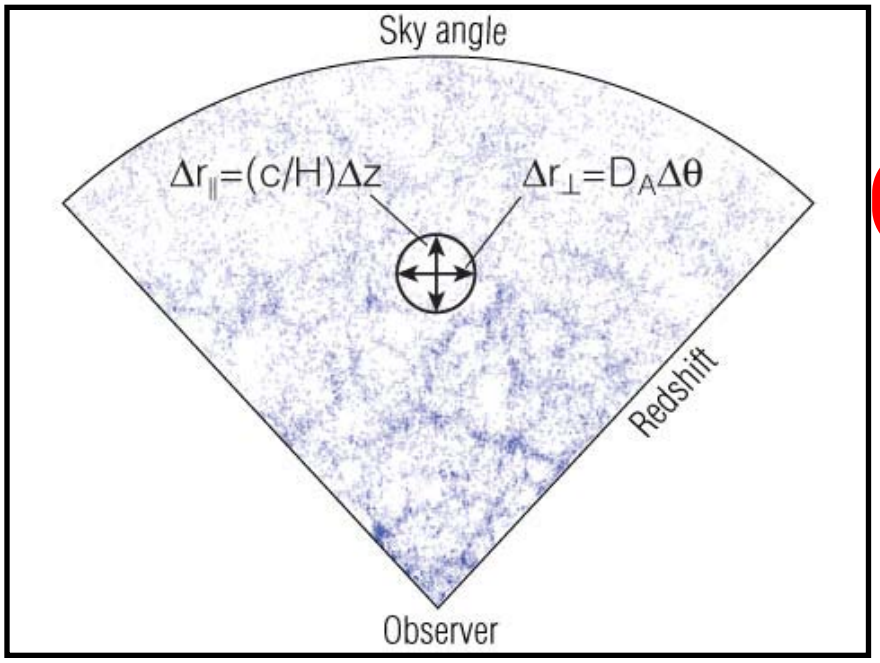
BAO and Dark Energy

Baryon Acoustic Oscillations (BAO)

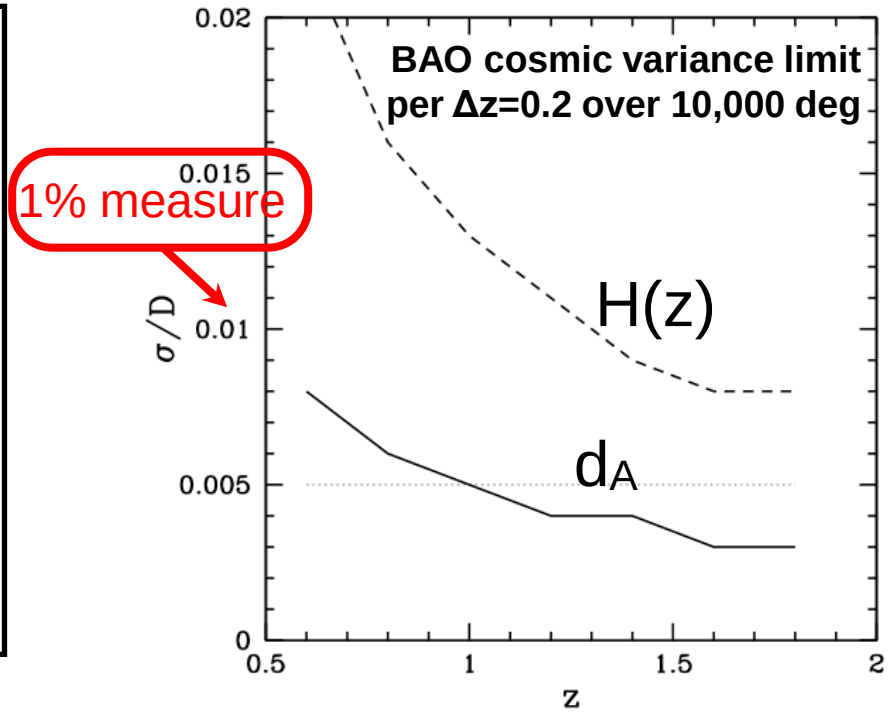
BAO measures 2 geometrical rulers:

- angular diameter distance (d_A)
- line-of-sight (Hubble constant)

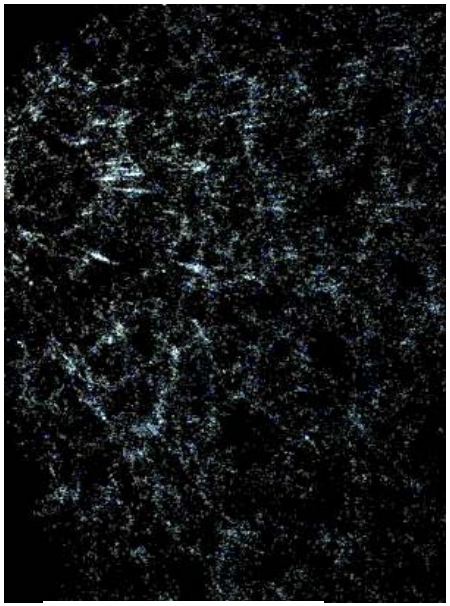
Improves ***linearly*** with ***Survey Area, Number of Galaxies***, √Volume

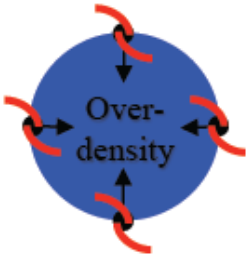


BigBOSS

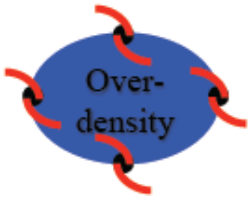


Redshift Space Distortions





Actual Shape



Apparent shape (viewed from below)

- 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 γ tests gravity separately from expansion history

$\gamma = 0.55$, GR

$\gamma \neq 0.55$, major discovery!

BigBOSS measures $\gamma \pm 0.02$

$$f(z)\sigma_8(z) \propto \Omega_m^\gamma \exp\left[\int \Omega_m^\gamma \, d\log a\right]$$

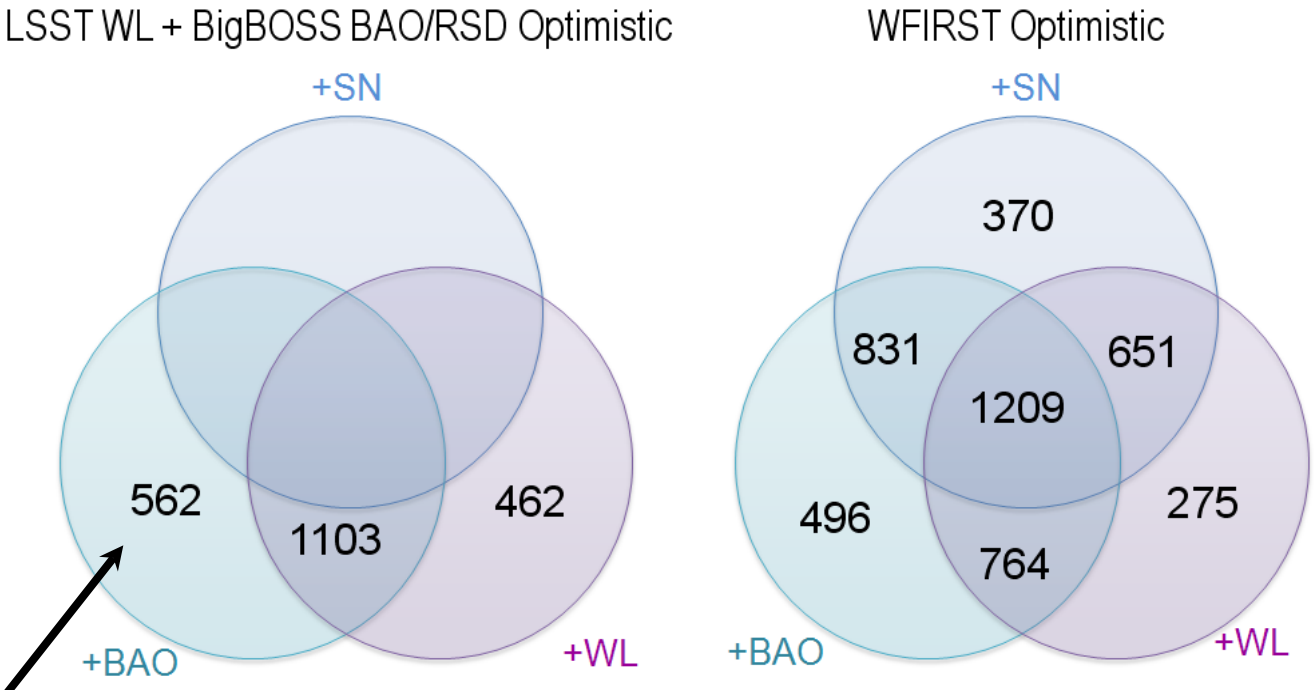
BOSS v BigBOSS

	BOSS	BigBOSS
Telescope	SDSS 2.5m	KPNO 4m
Number of simultaneous spectra	1000 (by hand)	5000 (by robot)
Survey duration	2009-2014	2017-2022
Total number of galaxies	1.5 million	26 million
Area (sq. degrees)	10,000	14,000+
Distance precision from galaxy BAO	~1% in 2 redshift bins	~1% in 35 bins
Dark Energy Figure of Merit	30	690
Gravity Figure of Merit	-	2500
Sum of neutrino masses	-	σ ~ 0.024eV

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

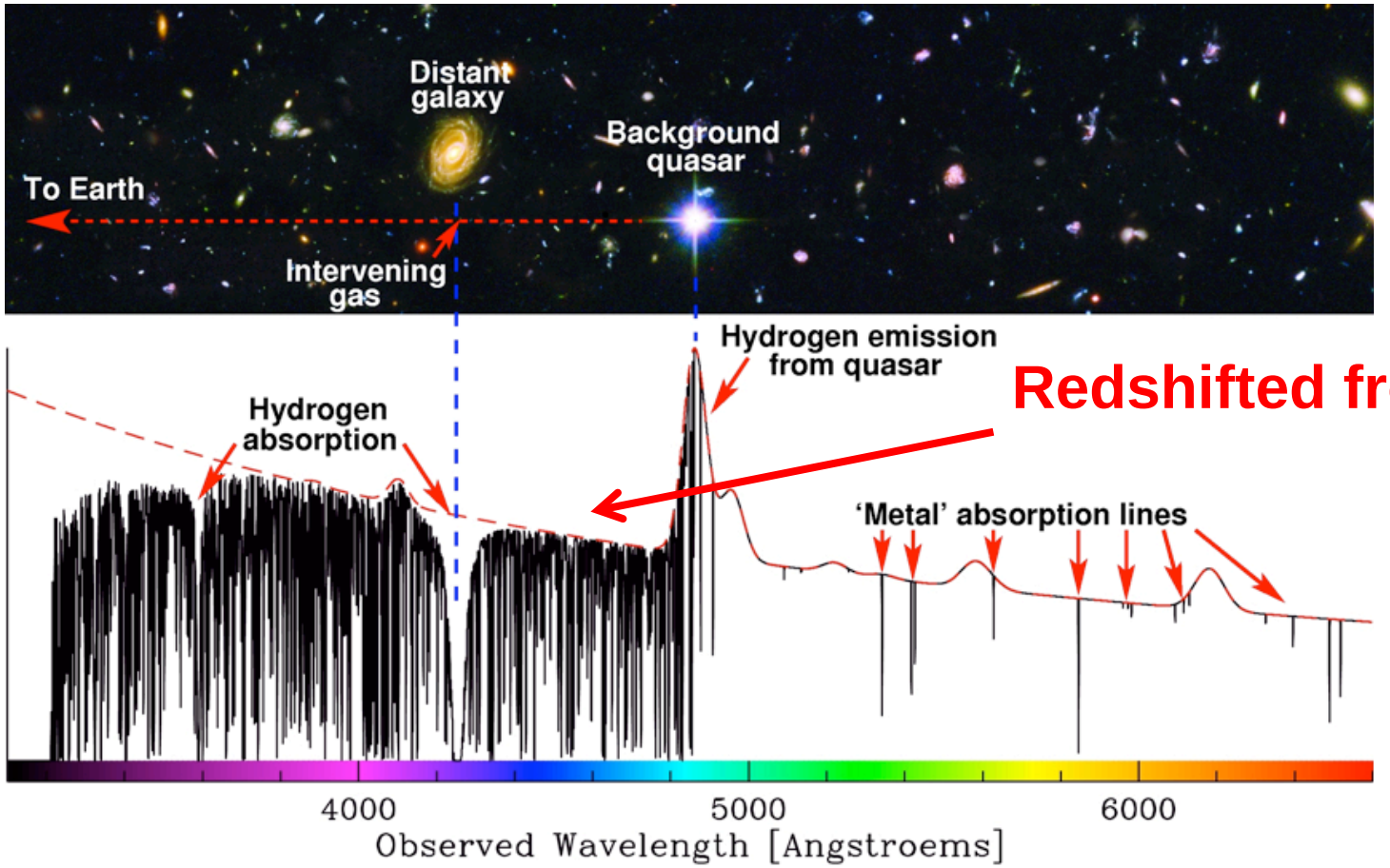


BigBOSS

Fig. reproduced from WFIRST Science Definition Team report
http://wfirst.gsfc.nasa.gov/science/WFIRST_Interim_Report.pdf

Ly-α Forest

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

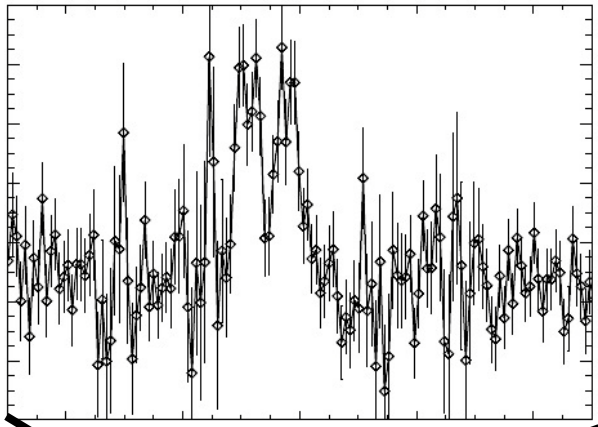


Emission Line Galaxies (ELGs)

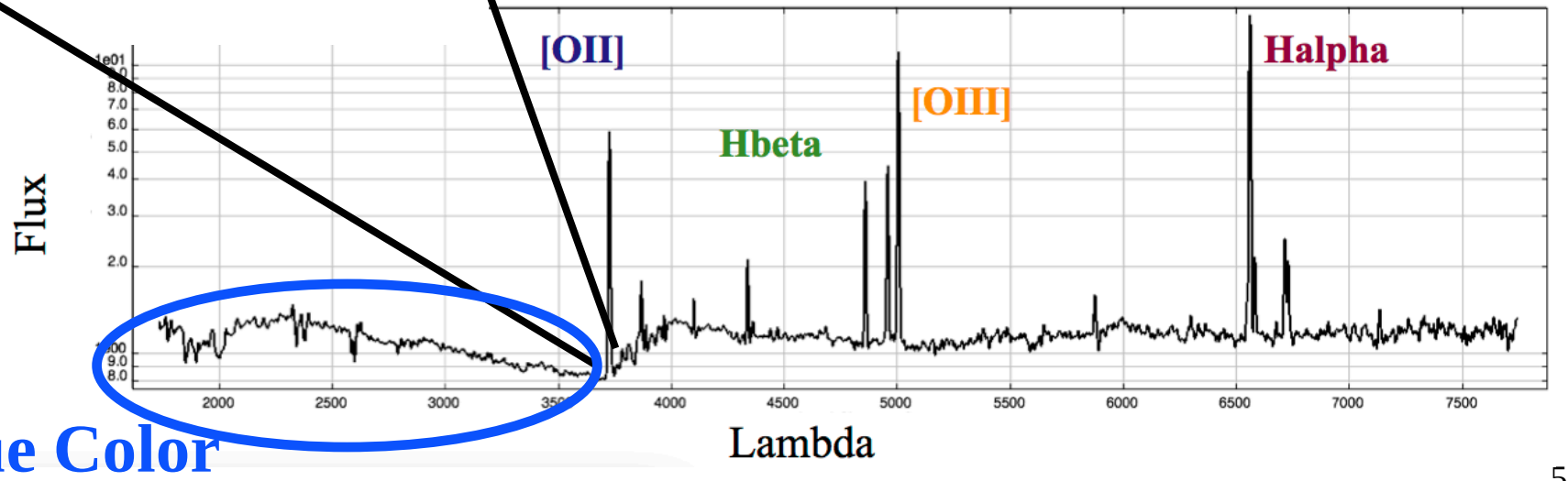
ELGs unique signature of [O II] doublet, detectable from z=0 to z=1.6

Well-studied, BigBOSS has taken data to prove these

ELGs drive BigBOSS wavelength coverage, throughput, & resolution



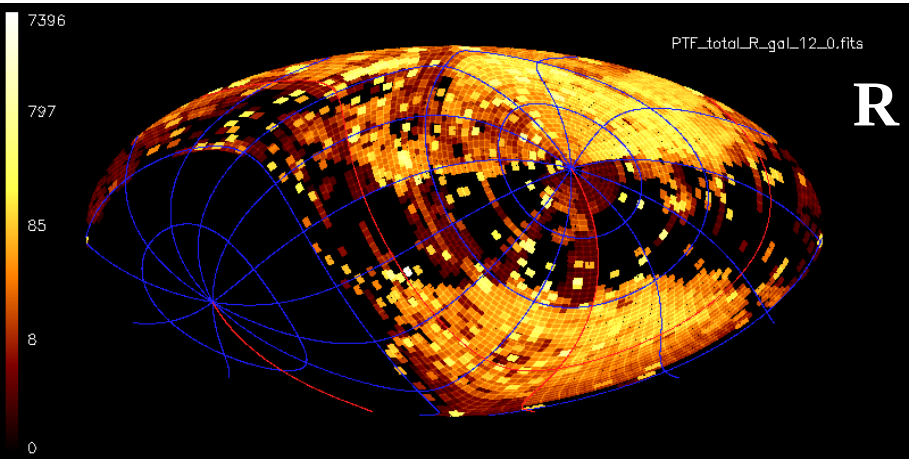
[O II] doublet at 3726.032 + 3728.815 Ang
BigBOSS detects to z=1.6 at 9700 Ang

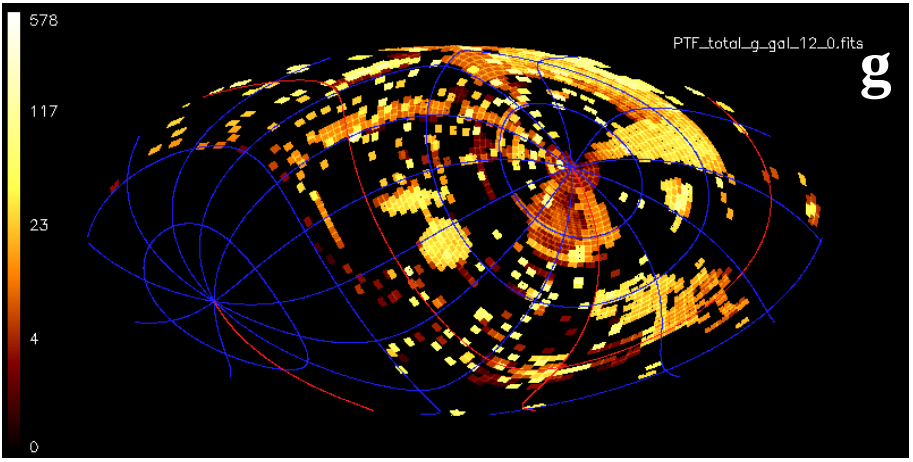


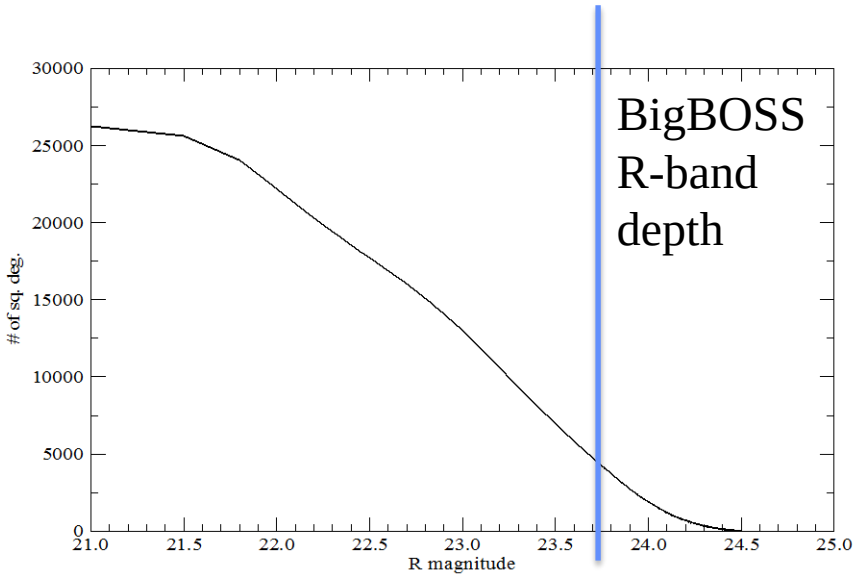
Blue Color

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 imaing data (PTF), and verified with VLT spectroscopy
- This demonstration was required by our review panels.







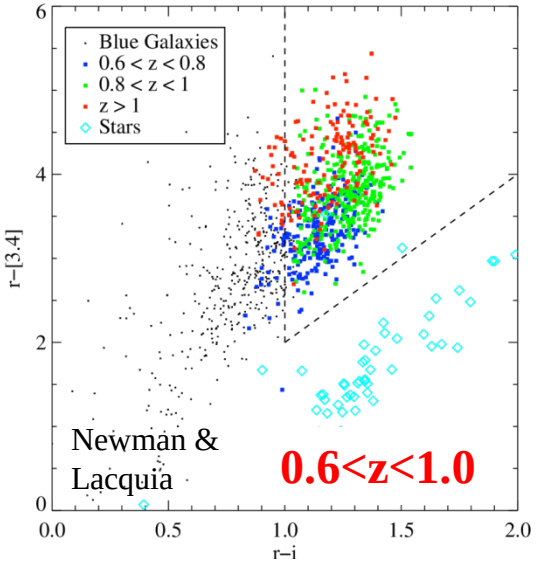
Current PTF sky coverage for BigBOSS

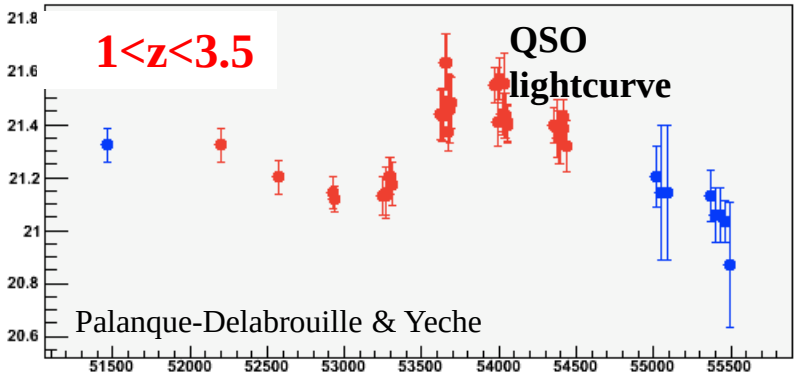
- ~ 5000 sq. deg with R-band depth
- ~ 1000 sq. deg with g-band depth

Target Selection

BigBOSS target selection is based on optical+NIR data from SDSS, PTF, and *WISE*

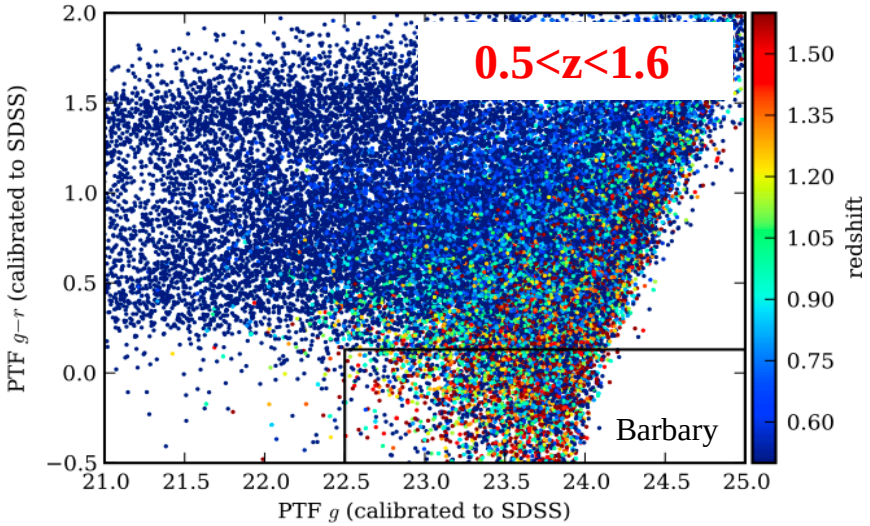
4 million Luminous Red Galaxies

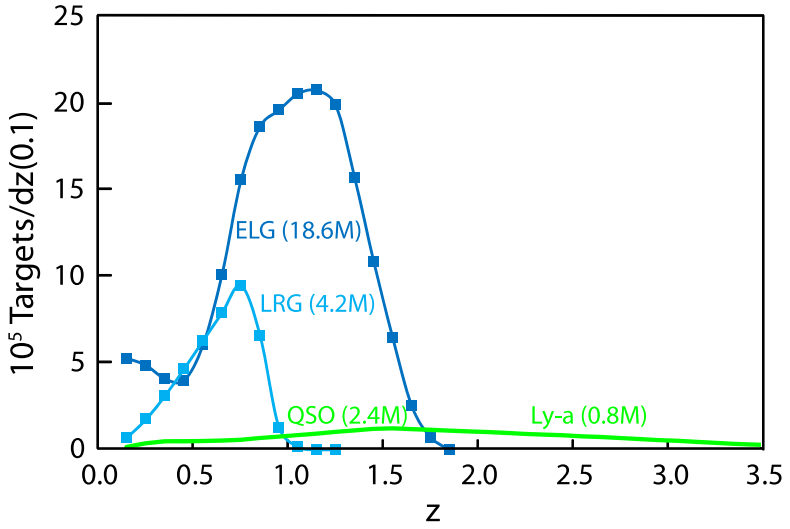




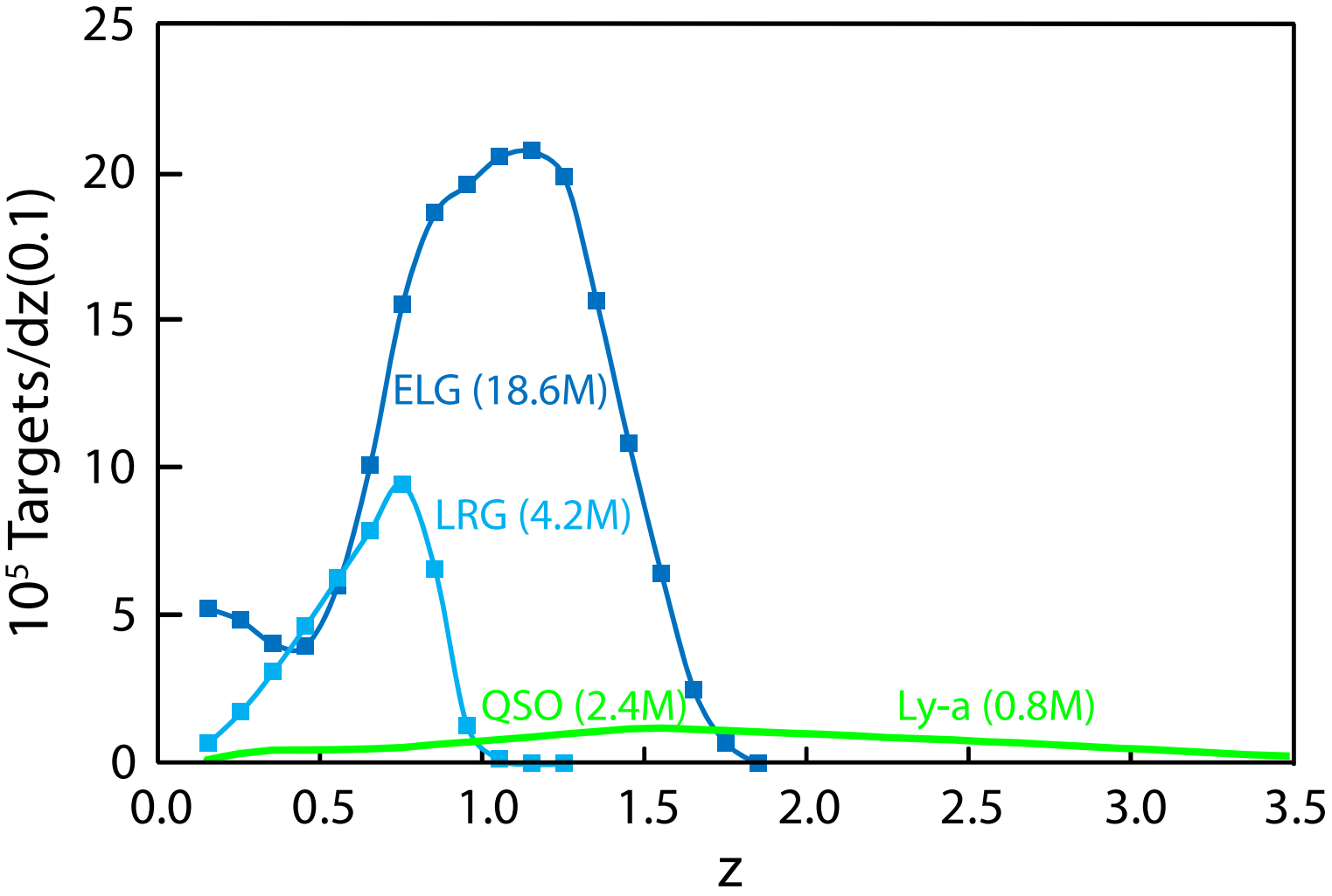
2.5 million Quasars

18 million Emission Line Galaxies

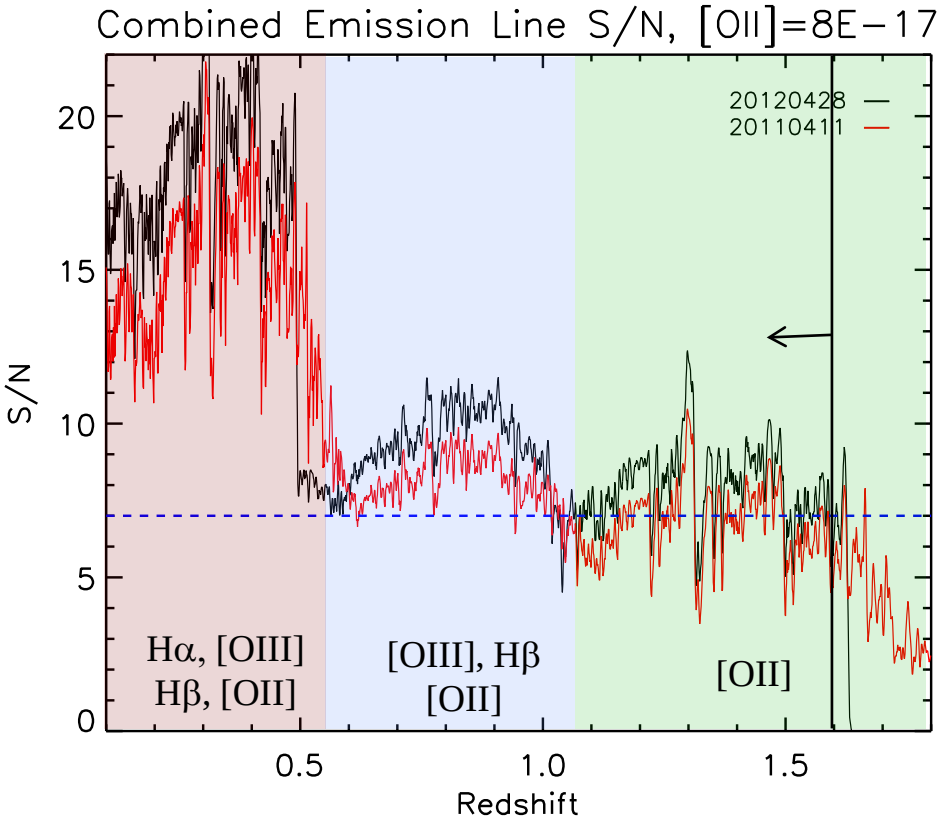




Target Distribution

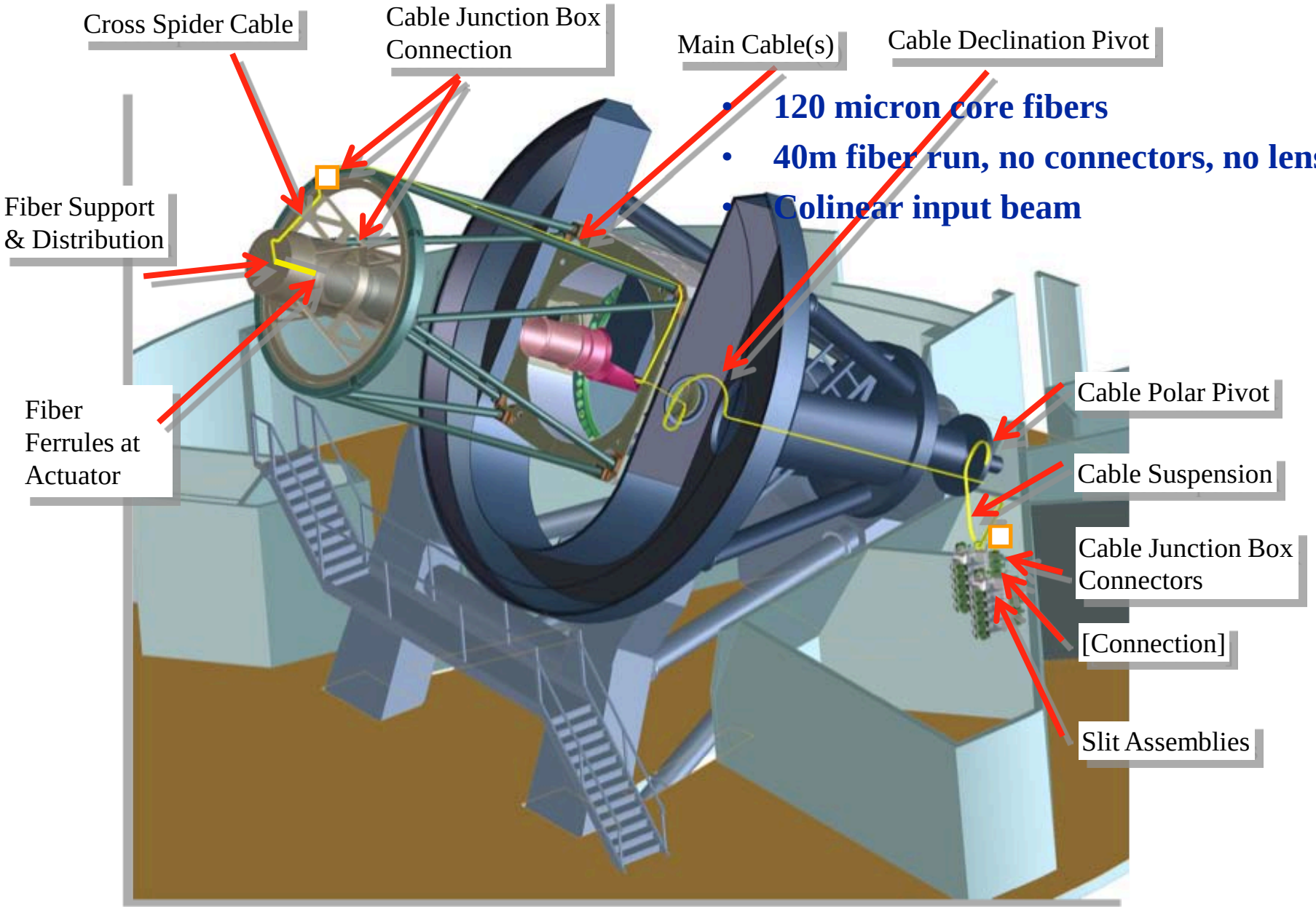


Simulation: Emission Line S/N vs redshift



- Simulated end-to-end performance
- Generate redshifts with line estimates for Lyα, [OII], Hβ, [OIII], and Hα
- Fit emission line templates for each line and redshift

Fiber System

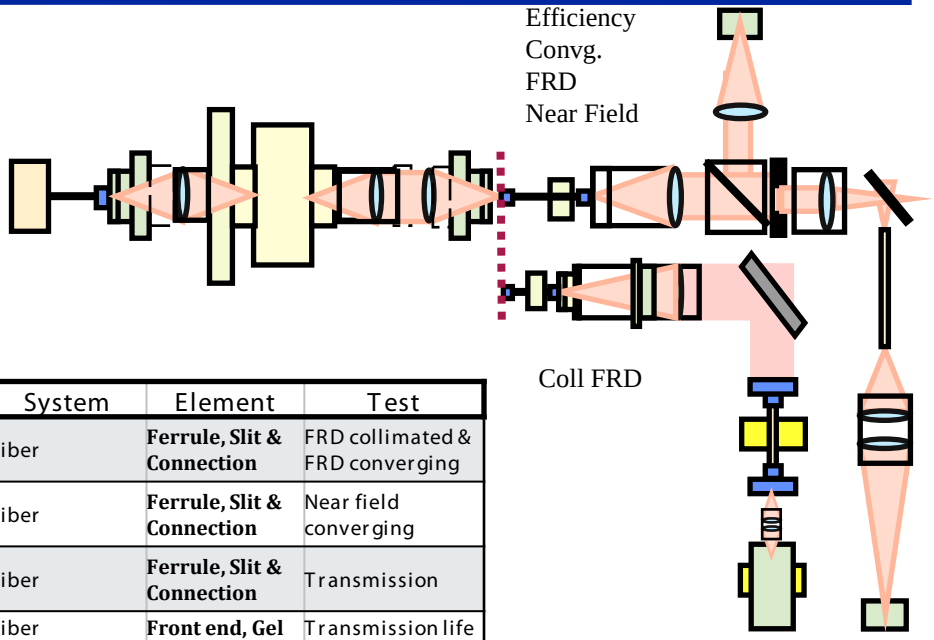


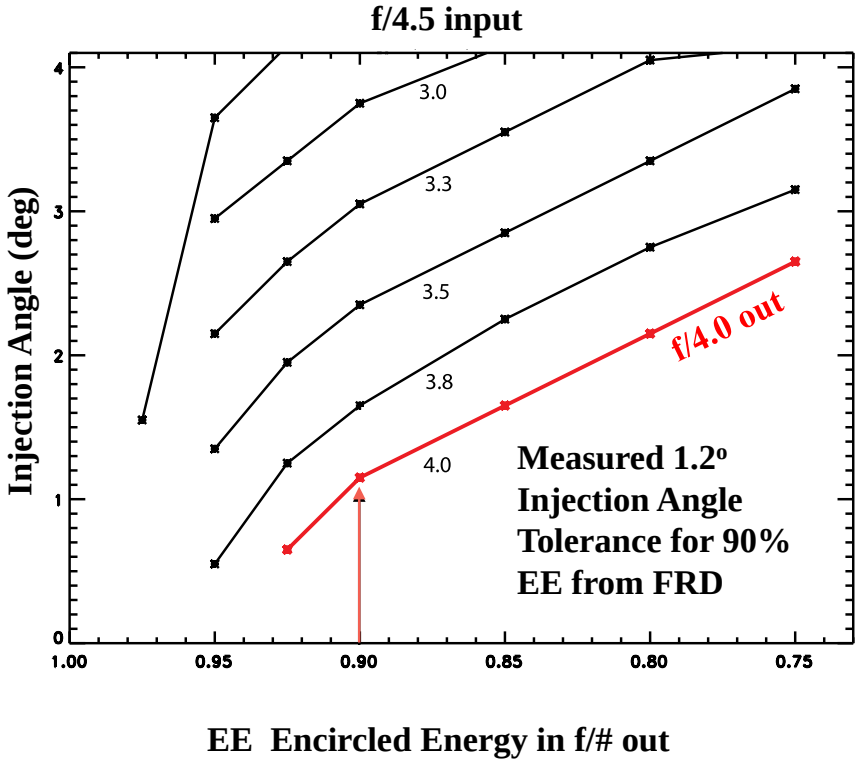
- **120 micron core fibers**
- **40m fiber run, no connectors, no lenslets!**
- **Colinear input beam**

Fiber Performance Testing

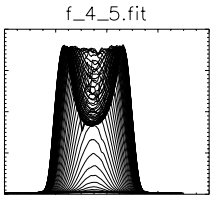
Evaluation & Performance Test

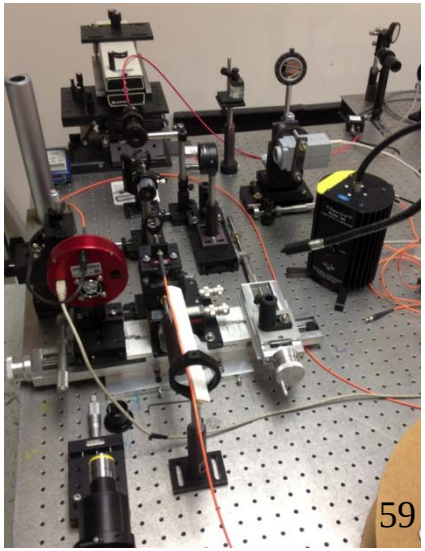
- Verify Science performance parameters
- Establish Instrument & Component Tolerance & Life
- Validate components & simulations
- Establish manufacturers' test methods





System	Element	Test
Fiber	**Ferrule, Slit & Connection**	FRD collimated & FRD converging
Fiber	**Ferrule, Slit & Connection**	Near field converging
Fiber	**Ferrule, Slit & Connection**	Transmission
Fiber	**Front end, Gel**	Transmission life
Fiber & Spectrograph	**Ferrule, Slit Grating, Dichroic**	AR coating throughput
Spectrograph	**Grating**	Efficiency
Spectrograph	**Grating**	Scatter: Near & Far Field
Spectrograph	**Dichroic**	Efficiency, Wavefront





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.**

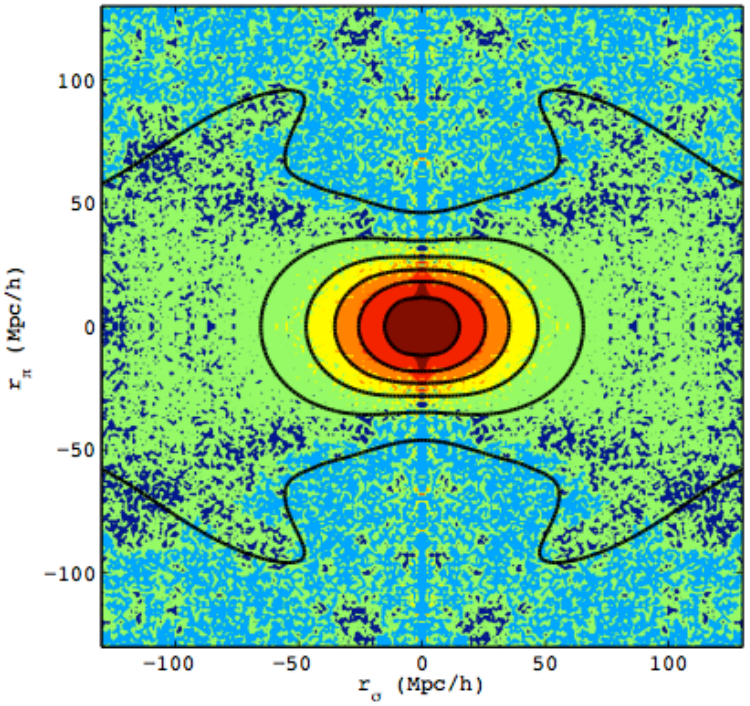
NSF/AST Portfolio Review

- **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]**

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

BOSS galaxies at z=0.57



Correlation functions would be circular if no gravitational growth

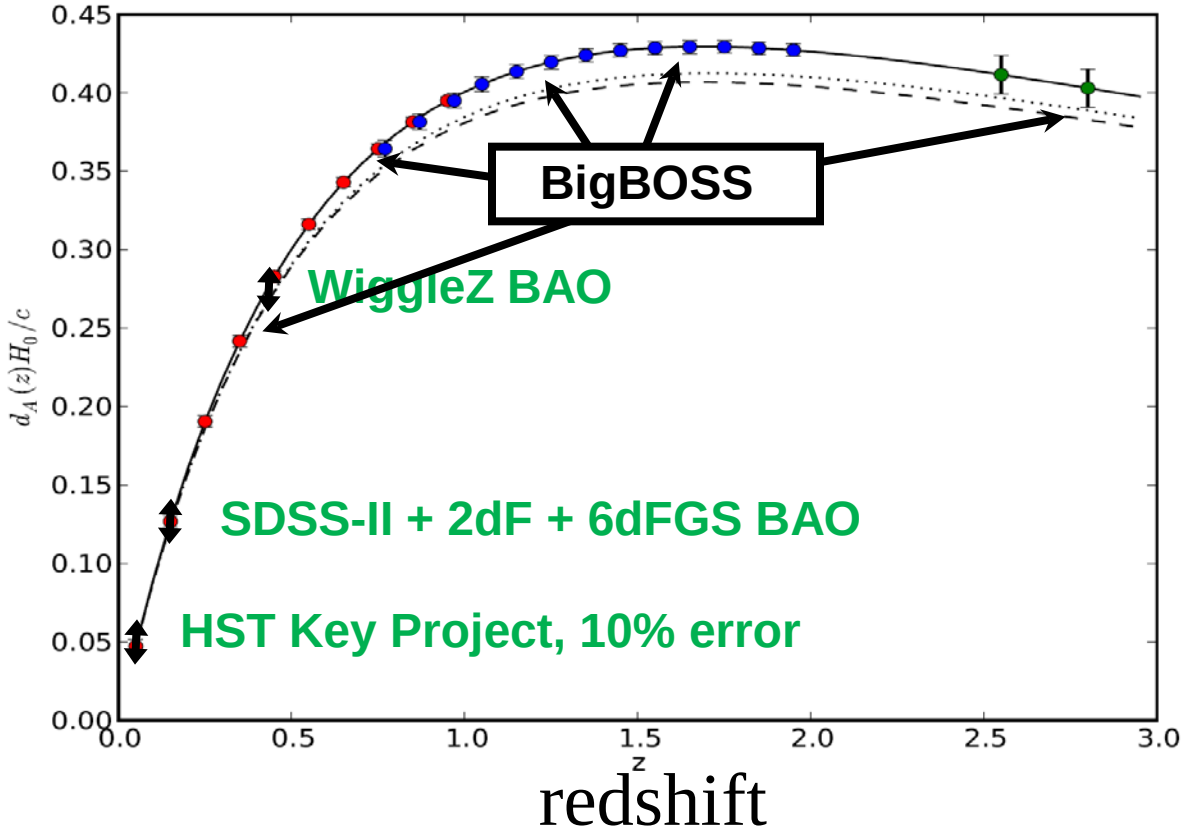
First results from Reid et al (2012)

BigBOSS science reach: BAO

Dark energy from Stage IV BAO

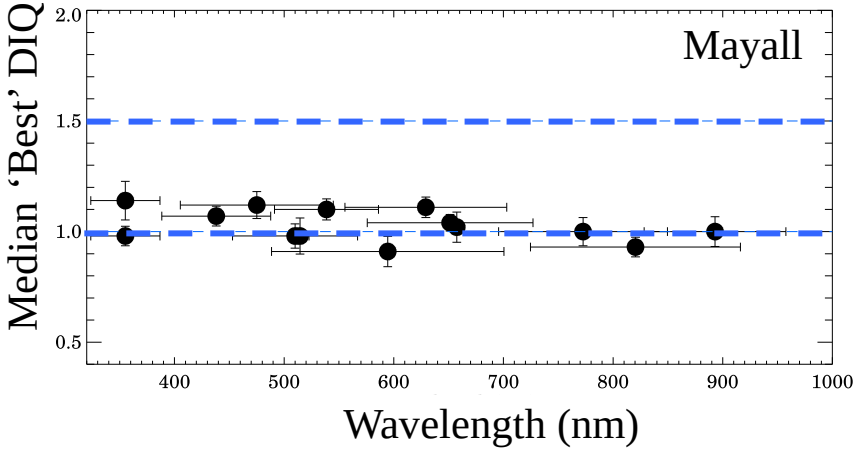
—*Geometric probe with 0.3-1% precision from z=0.5 -> 3*

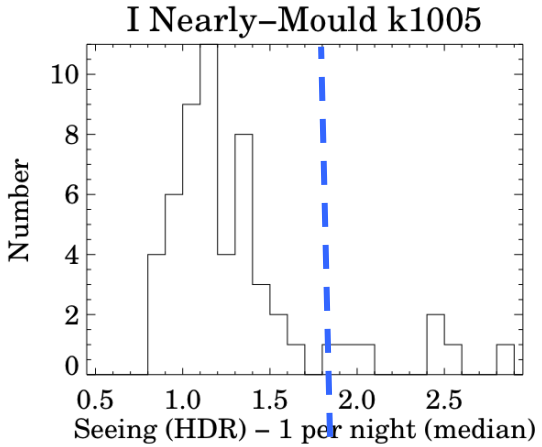
BigBOSS BAO "Hubble diagram"



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