BOSS
BigBOSS
and beyond

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Outline:

- Maps: What's possible?
- SDSS-III/BOSS design, z=0 → 0.7, 2.3
- SDSS-III/BOSS 1st results
- BigBOSS design, z=0 → 3.5
- Some warnings analyzing future data!

Fitting the Universe

Linear vs. non-linear

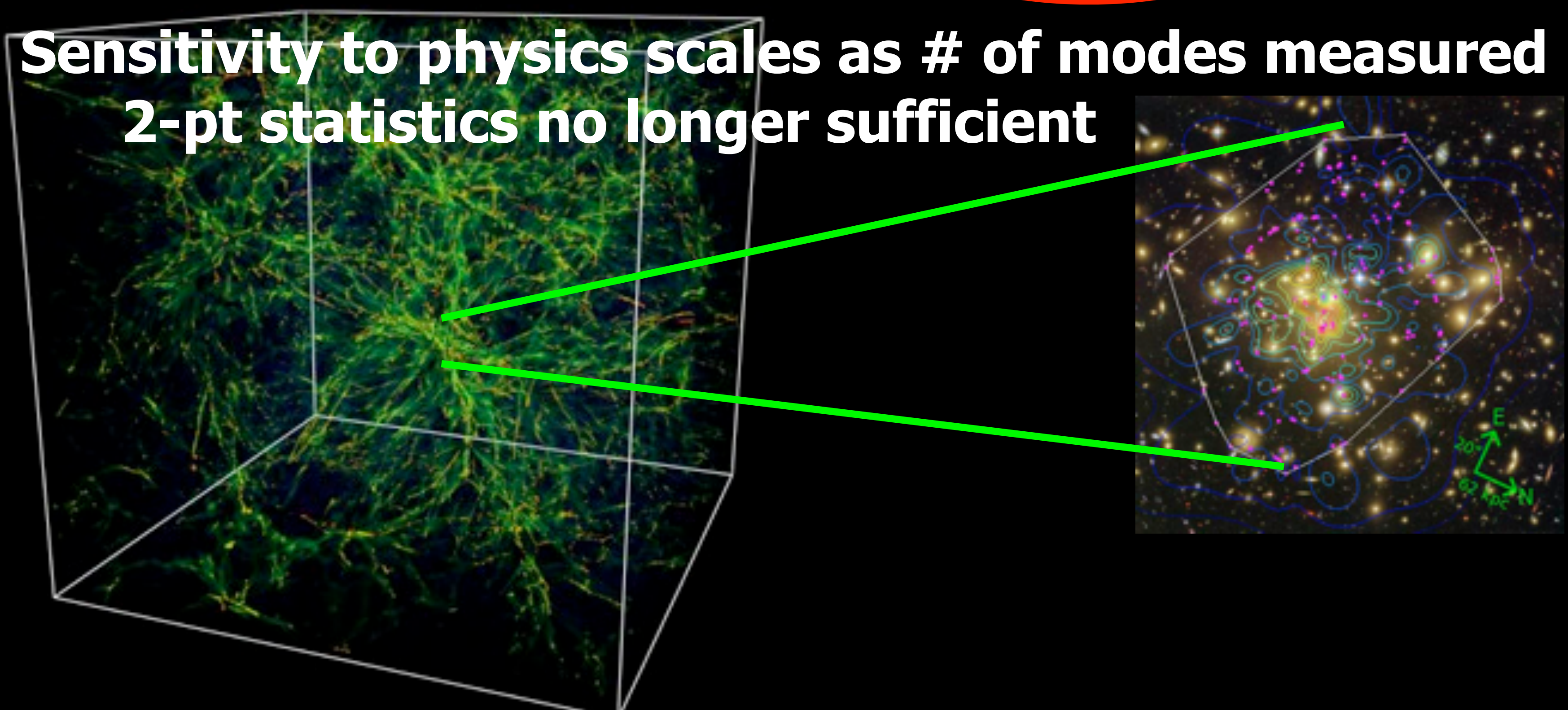
Early Universe fluctuations ↔ linear modes

How many linear modes?

$\sim 4\pi(1000\ \mathrm{Mpc}/8\ \mathrm{Mpc})^3 \approx$ 100 million to z=1

Sensitivity to physics scales as # of modes measured

2-pt statistics no longer sufficient



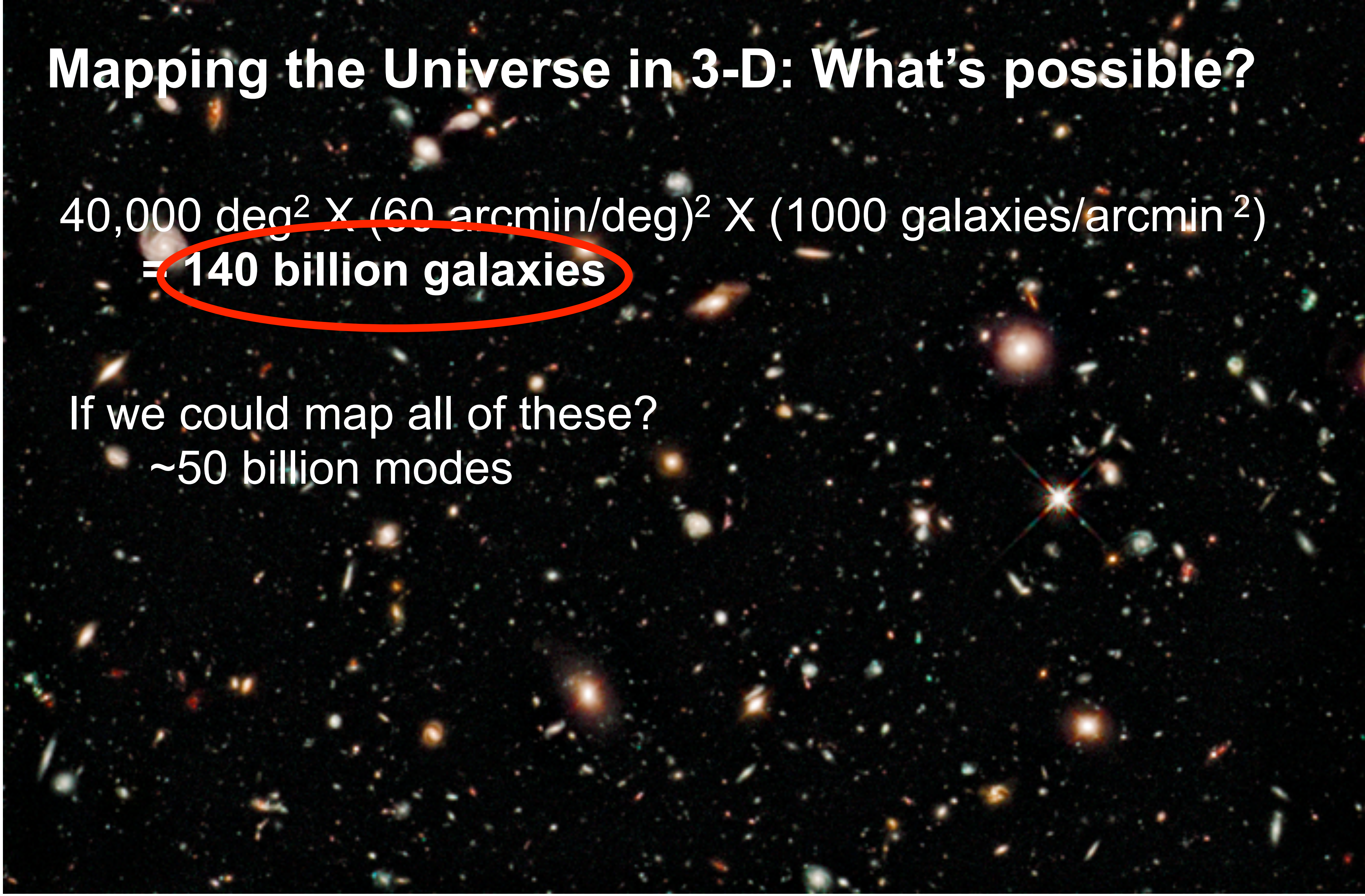
Mapping the Universe in 3-D: What’s possible?

40,000 deg^2 X (60 arcmin/deg)^2 X (1000 galaxies/arcmin ^{2})

= 140 billion galaxies

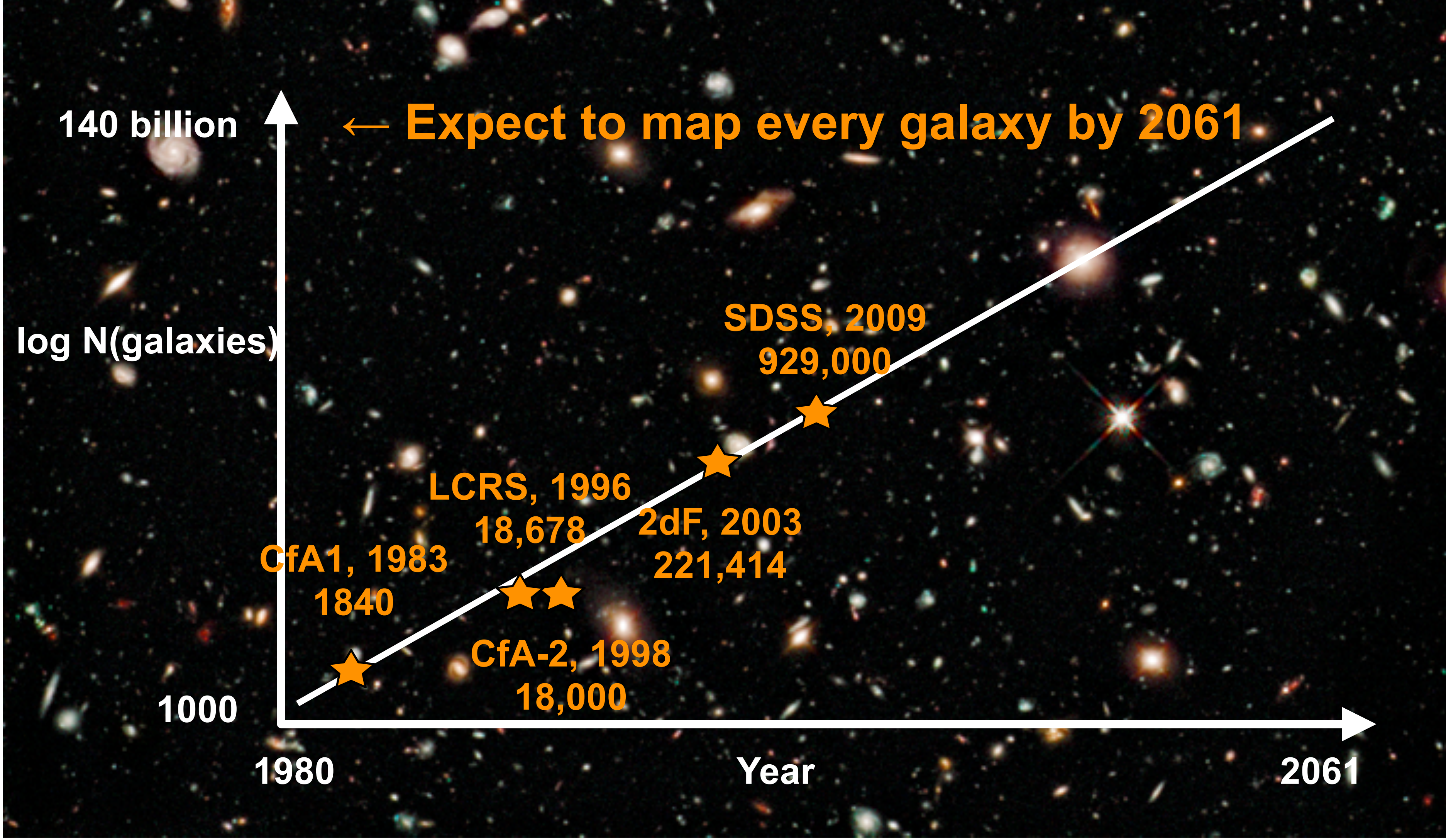
If we could map all of these?

~50 billion modes



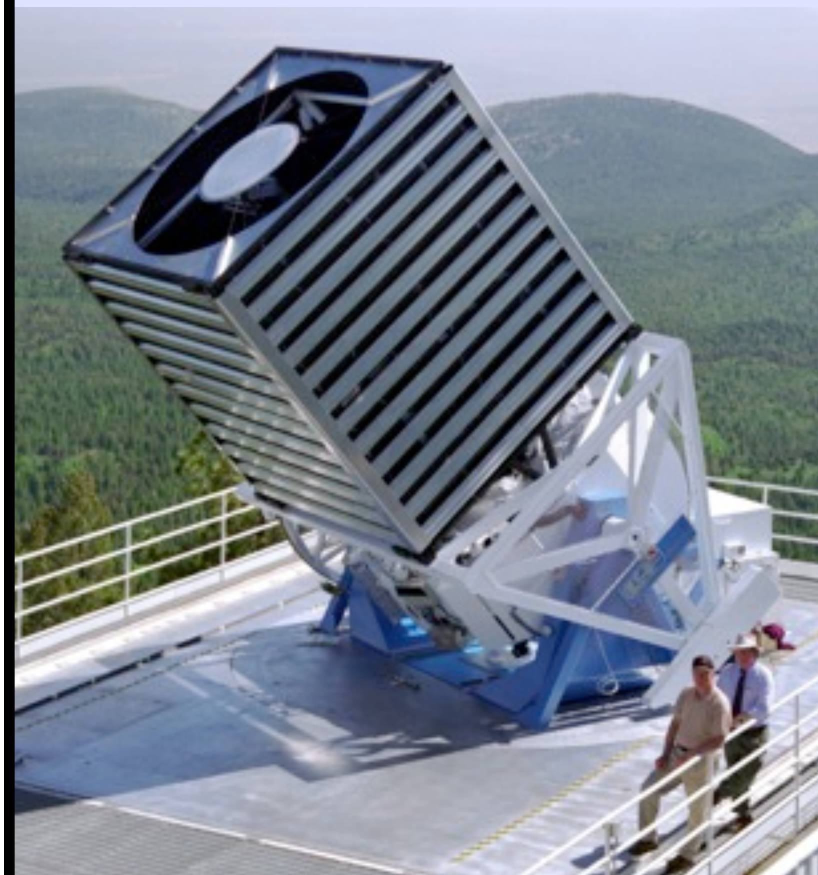
HST Ultra-Deep Field
10,000 galaxies / (11 arcmin^2)

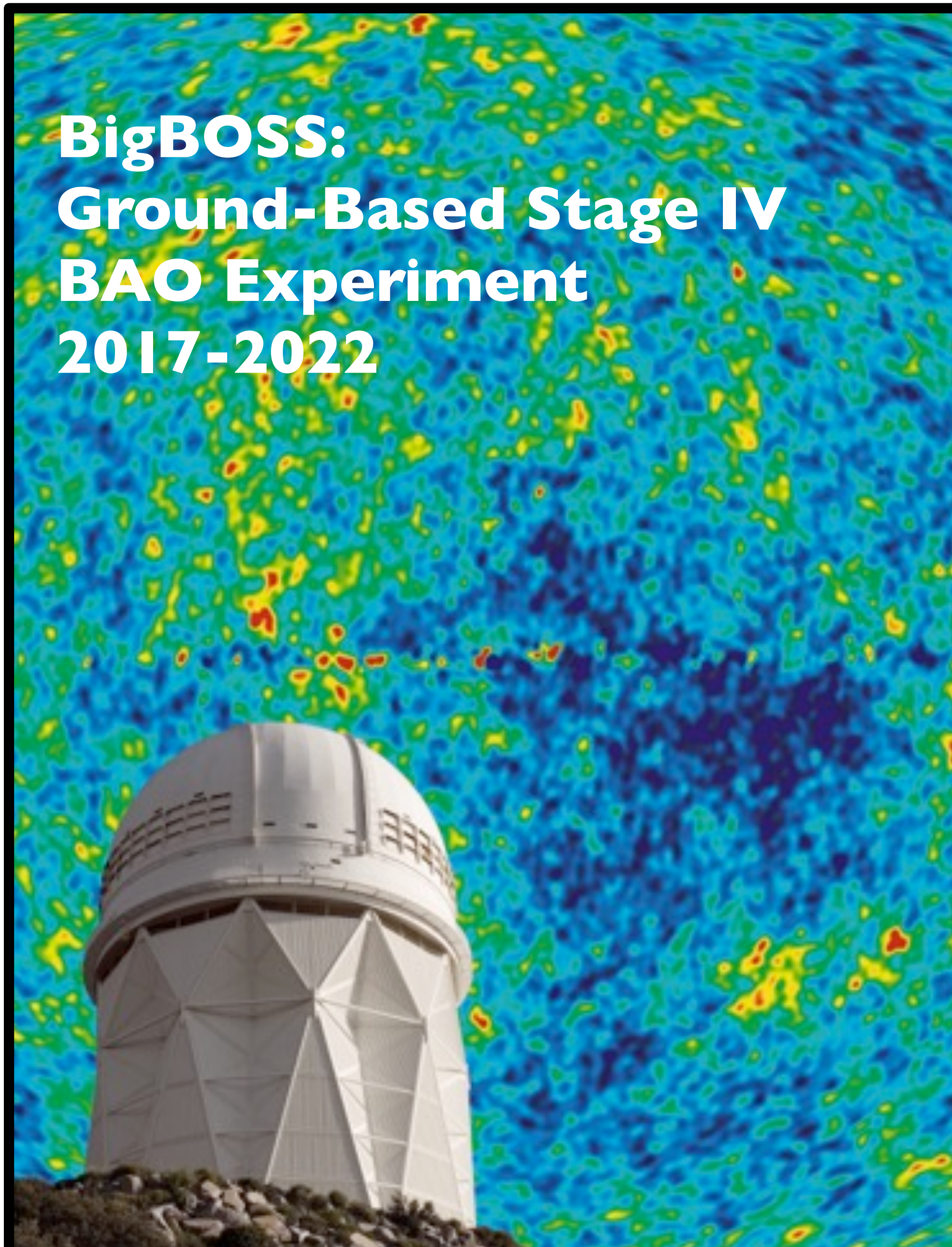
Mapping the Universe in 3-D: What's possible?



HST Ultra-Deep Field
10,000 galaxies / (11 arcmin^2)

BOSS:
Ground-Based Stage III
BAO Experiment
2008-2014





BOSS:
Ground-Based Stage III BAO Experiment
2008-2014

Rebuilt SDSS-III spectrographs:

3 deg diameter field of view
1000 fiber positioners
3600-10,000 Ang at resolution~2000

Conduct BOSS Key Project

5 years dark time
10,000 deg^2 imaging
1.5 million galaxy spectra
160,000 QSO spectra at z>2.1

Fall 2009 - 2014

All data public 1 year later

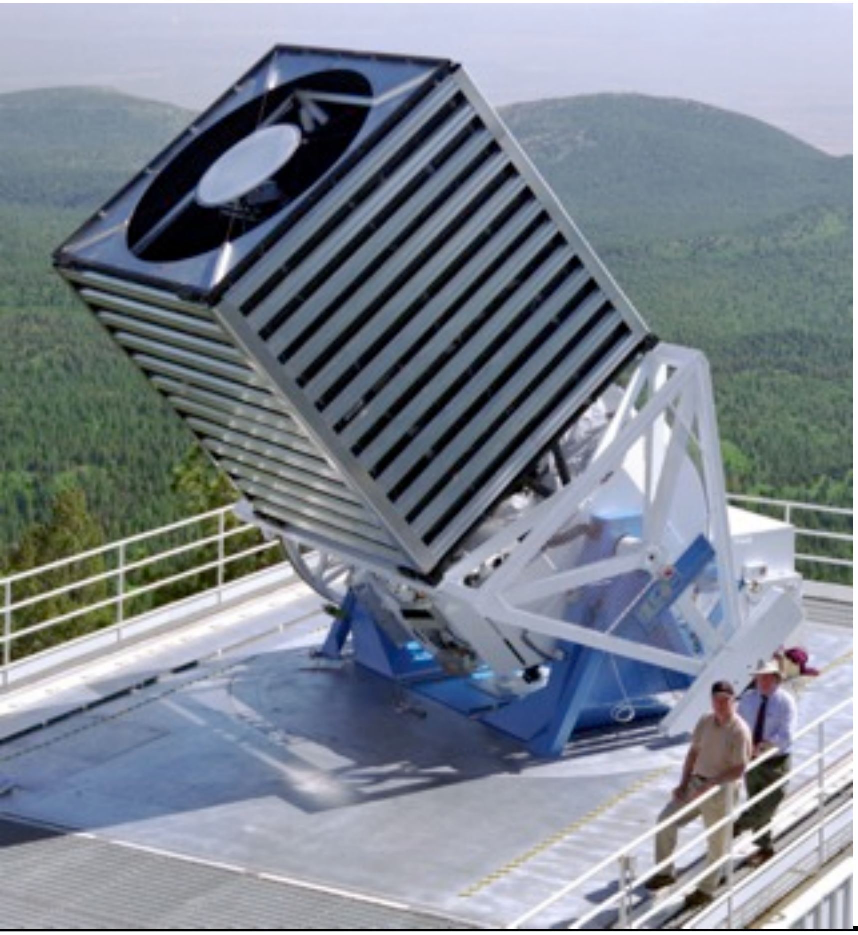
BOSS: Baryon Oscillation Spectroscopic Survey

SDSS-III Collaboration: BOSS + SEGUE + MARVELS + APOGEE

- University of Arizona
- Brazilian Participation Group (ON, UFRGS, UFRN, UFRJ)
- Brookhaven National Lab (a)
- Cambridge University
- Carnegie Mellon University (a)
- Case Western University (a)
- Fermilab (a)
- University of Florida
- French Participation Group (APC, IAP, CEA, LAM, Besancon)
- German Participation Group (AIP, MPE, MPIA, ZAH)
- Harvard University
- Instituto de Astrofisica de Canarias
- MULTIDARK - Institito de Astrofisica de Andalucia, Granada (a)
- Instituto de Fisica Corpuscular, Valencia (a)
- Institucio Catalana de Recerca y Estudis Avancat, Barcelona (a)
- University of California, Irvine (a)
- Johns Hopkins University
- **Korean Institute for Advanced Study** (a)
- Lawrence Berkeley National Laboratory
- Max Planck Astrophysics (MPA)
- Michigan State/Notre Dame/JINA Participation Group
- New Mexico State University
- New York University
- Ohio State University
- Penn State University (a)
- University of Pittsburgh (a)
- University of Portsmouth
- Princeton University
- Texas Christian University (a)
- University of California, Santa Cruz (a)
- University of Tokyo
- University of Utah
- University of Virginia
- University of Washington
- University of Wisconsin (a)
- Vanderbilt University
- Yale University

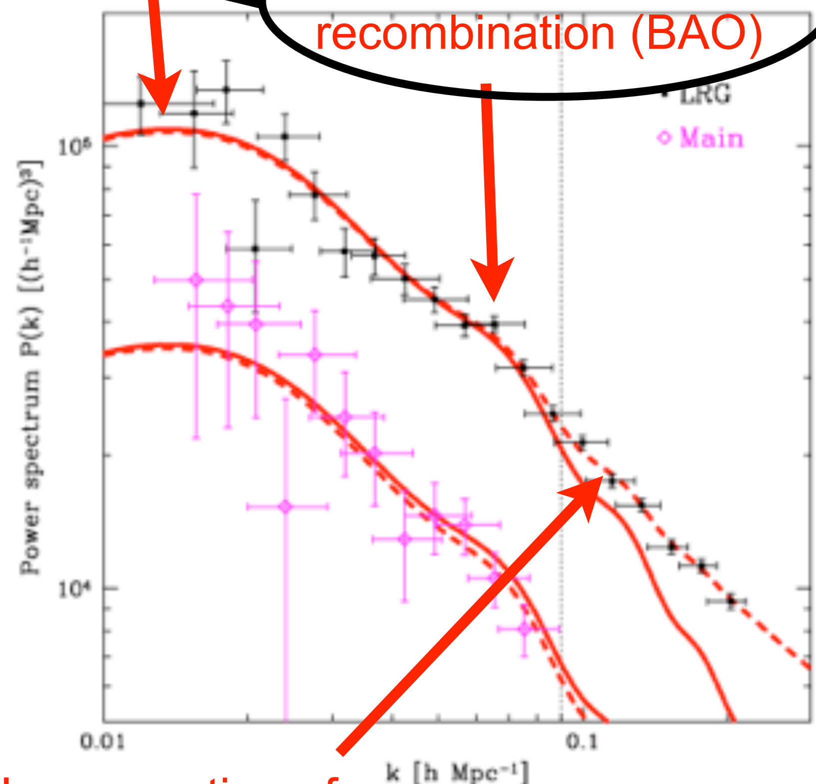
BOSS:
Mapping the linear modes z < 0.7

BOSS survey designed to measure BAO feature



Turn-over depends upon horizon size at matter-radiation equality

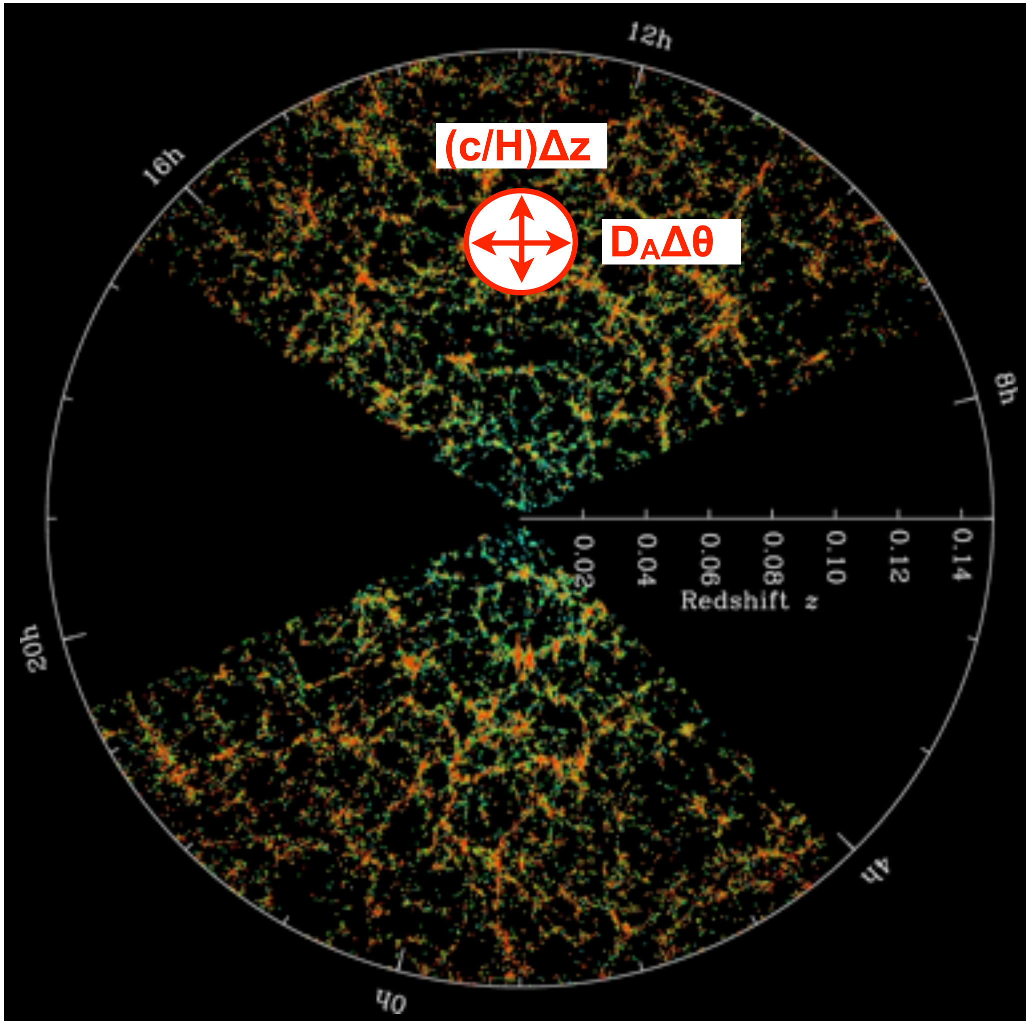
Sound horizon scale at recombination (BAO)



Galaxy halo occupation of dark matter halos (HOD)

BAO and dark energy

BOSS measures BAO in 3-D maps



BAO measures two standard rulers:

- o Angular diameter distance, $\mathbf{D_A}$
- o Line-of-sight Hubble parameter, **H**

Gravity measured from redshift-space distortions (RSD)

D_A is the integral of H

$$H(z) = \sqrt{\Omega_M(1+z)^3 + (1-\Omega_M-\Omega_\Lambda)(1+z)^2 + \Omega_\Lambda}\,, \quad (2.4)$$

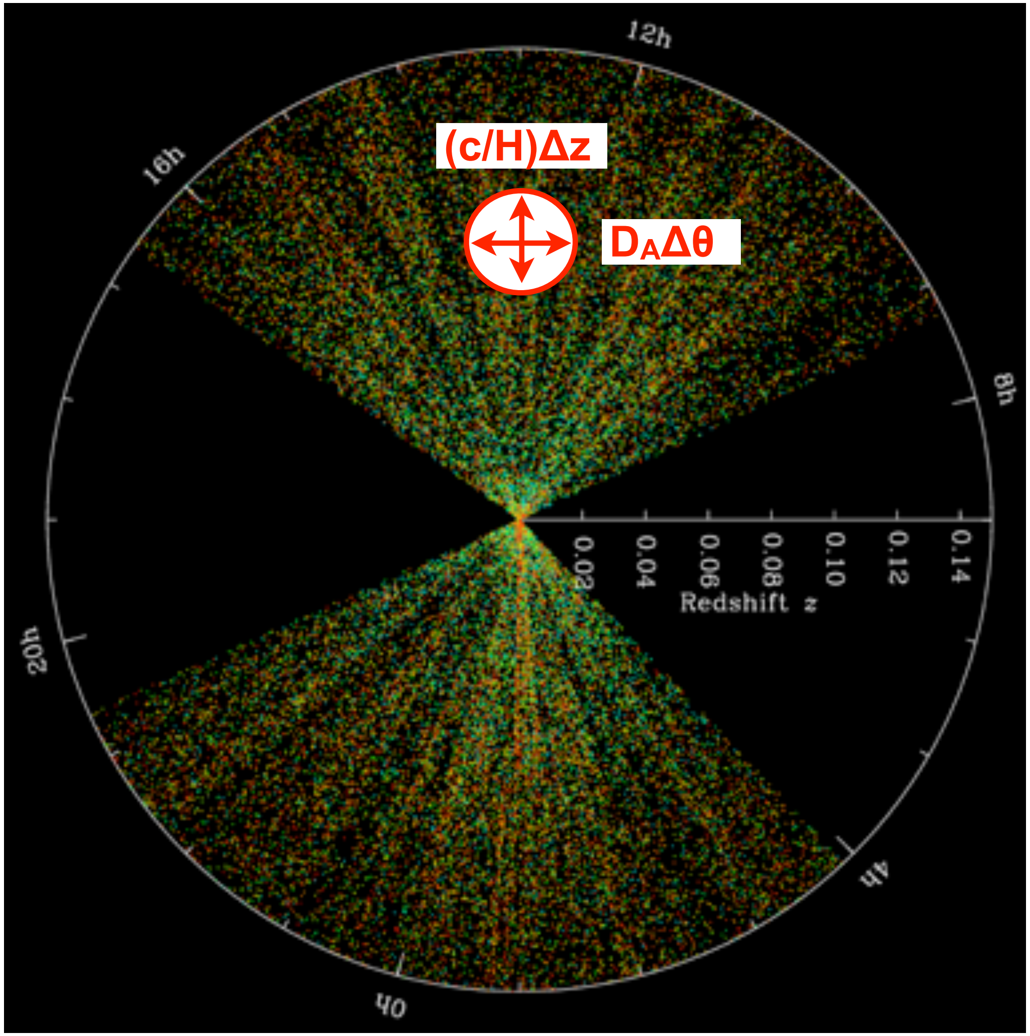
$$d_A(z) = \begin{cases} (-K)^{-1/2}\sinh\left[(-K)^{1/2}\chi(z)\right] & K<0\,, \\ \chi(z) & K=0\,, \\ K^{-1/2}\sin\left[K^{1/2}\chi(z)\right] & K>0\,, \end{cases} \quad (2.5)$$

where

$$K = 1-\Omega_M-\Omega_\Lambda, \qquad \chi(z) = \int_0^z \frac{dz'}{H(z')} \quad (2.6)$$

BAO and dark energy

BAO+RSD not competitive w/out spectroscopy

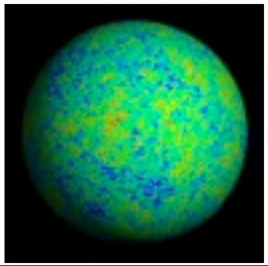


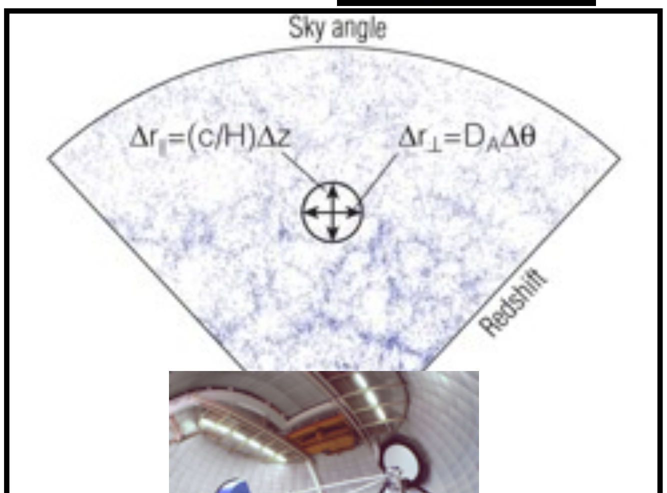
Imaging-only surveys can produce photo-z redshifts with errors Δz~0.03

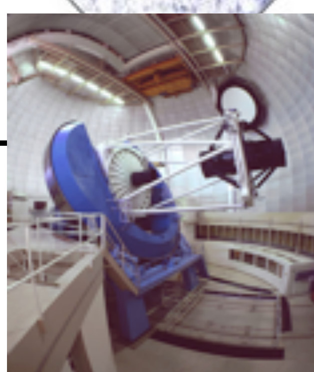
o BAO from D_A degraded by factor ~5
o BAO from H(z) not measured
o Gravity (RSD) not measured

BAO and dark energy

What tracer objects to use?







z=1087 — CMB: Planck will measure d_A to 0.1%

z=20 — H gas in 21-cm emission

z=5 — Ly-A emitter galaxies

QSO absorption lines

z=2

Galaxies,
galaxy clusters,
SNe

z=0

All existing BAO measurements

BAO and dark energy

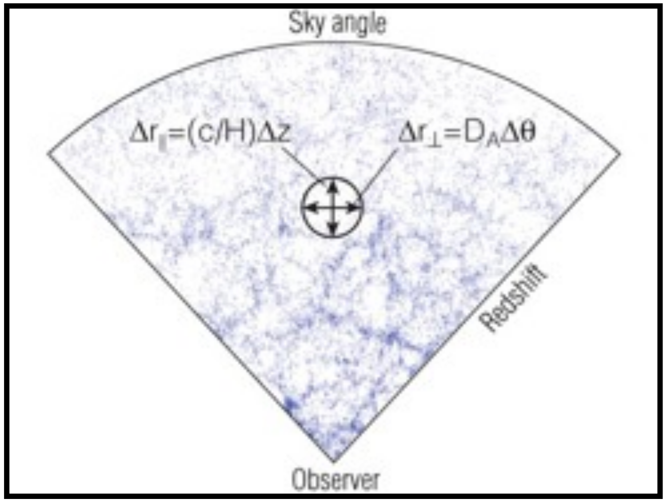
Density of tracers?

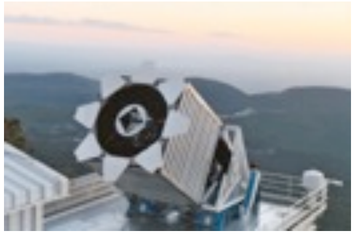
Requirement: Sample linear modes at 100 h^{-1}Mpc
Shot noise ~ (1 + 1/nP)

P = power at 100 Mpc
n = sampling density

Shot noise small if nP>3 ⇒ n > 1 per (10 h^{-1}Mpc)^{3}n

If tracers are ***biased*** relative to dark matter, we need even fewer (because P>1)





z=20 — H gas in 21-cm emission

z=5 — Ly-A emitter galaxies, QSO absorption lines

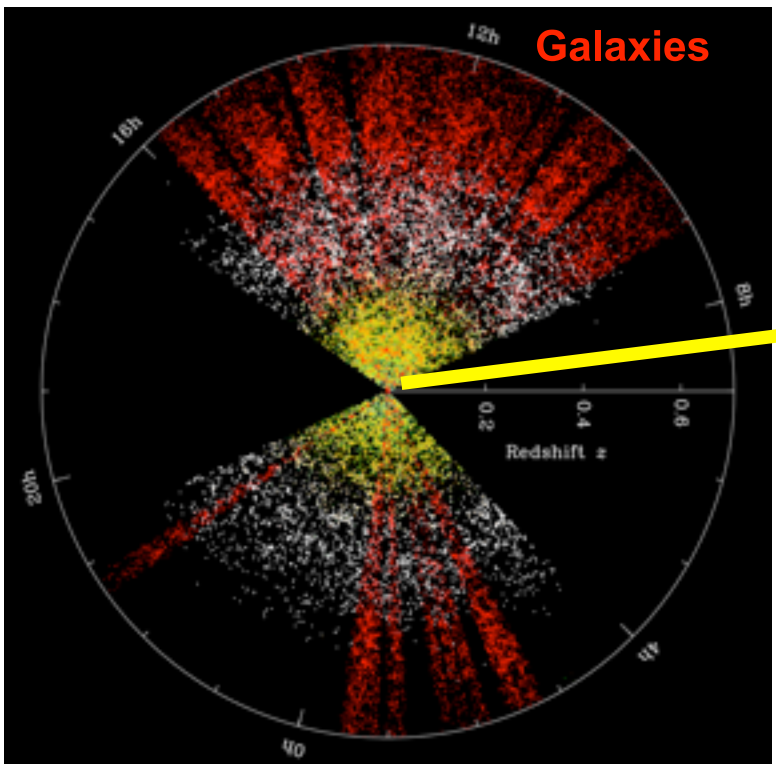
z=2 — Galaxies, galaxy clusters, SNe

z=0

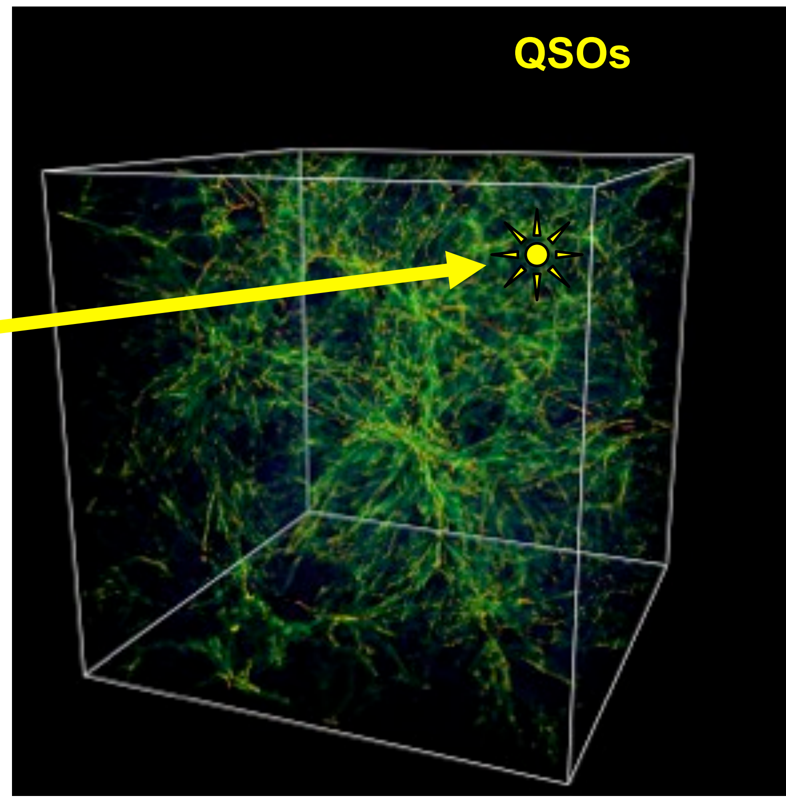
BOSS: Dark energy from 3-D maps

BOSS measures dark energy from the BAO "standard ruler"
1. Imaging survey of > 10,000 deg^2 for targets
2. Spectroscopic survey of 1.5 million galaxies at $0.15 < z < 0.7$
3. Spectroscopic survey of 160,000 QSOs at $2.1 < z < 3.5$

Definitive BAO experiment at z < 0.7
On track to complete in 2014

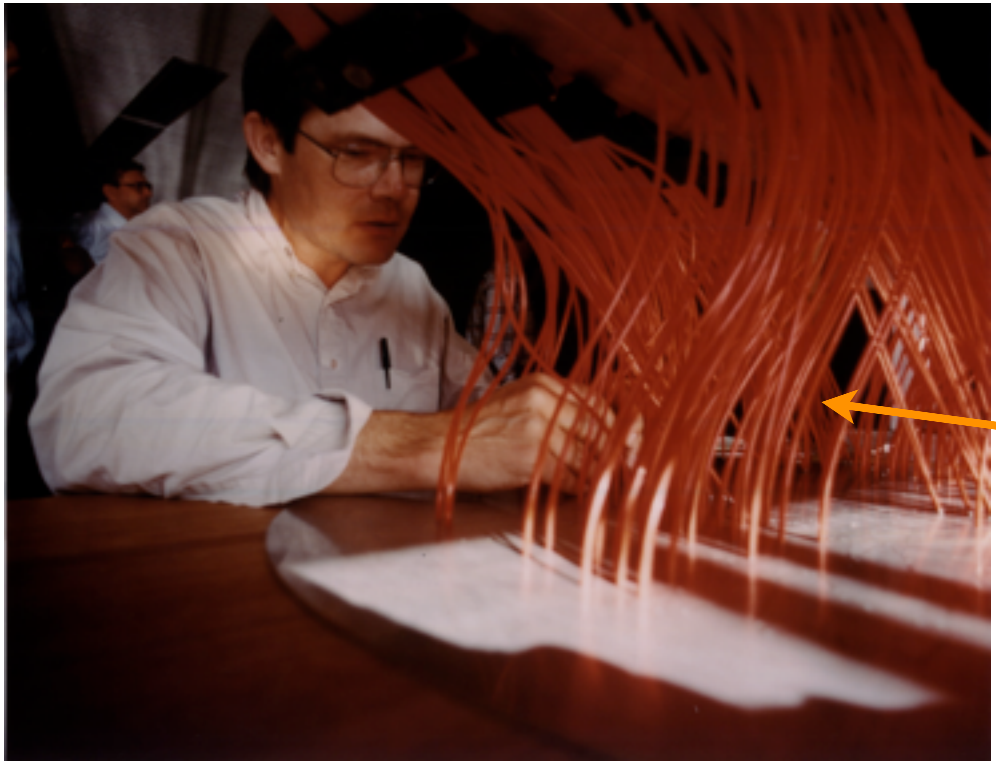


Pathfinder BAO experiment at z > 2
using hydrogen absorption to QSOs



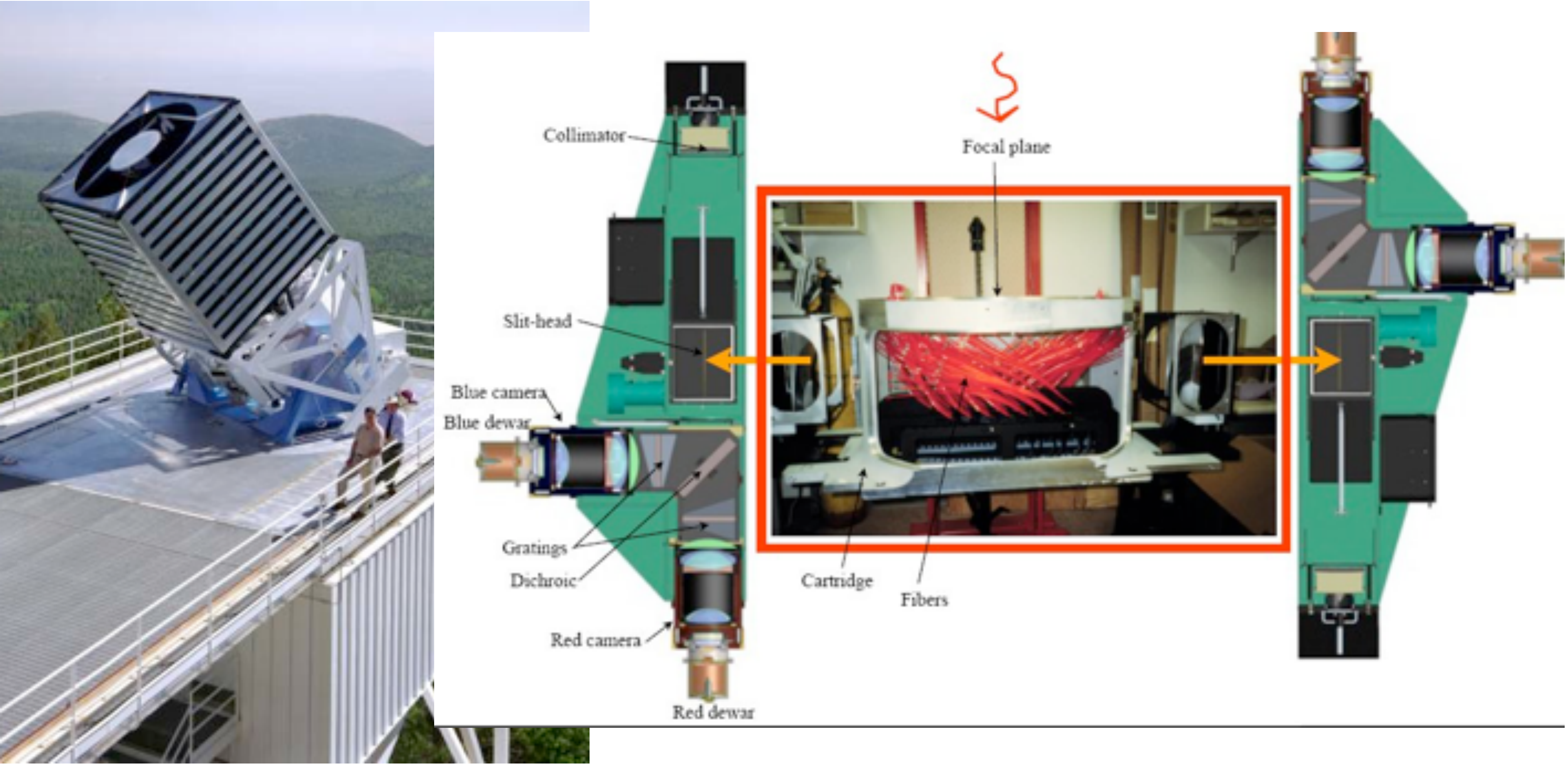
BOS on the Sloan Telescope

Plug-plates for fiber positioning
Spectrographs hang off telescope



BOSS major upgrade to spectrographs

o New CCDs, gratings, fiber system
o Greatly improved red throughput (for galaxies)
o Greatly improved blue throughput (for quasars)
o Increase multi-plexing (fiber count) to 1000
Completed Aug 2009: Best-in-world spectrograph for large-area surveys

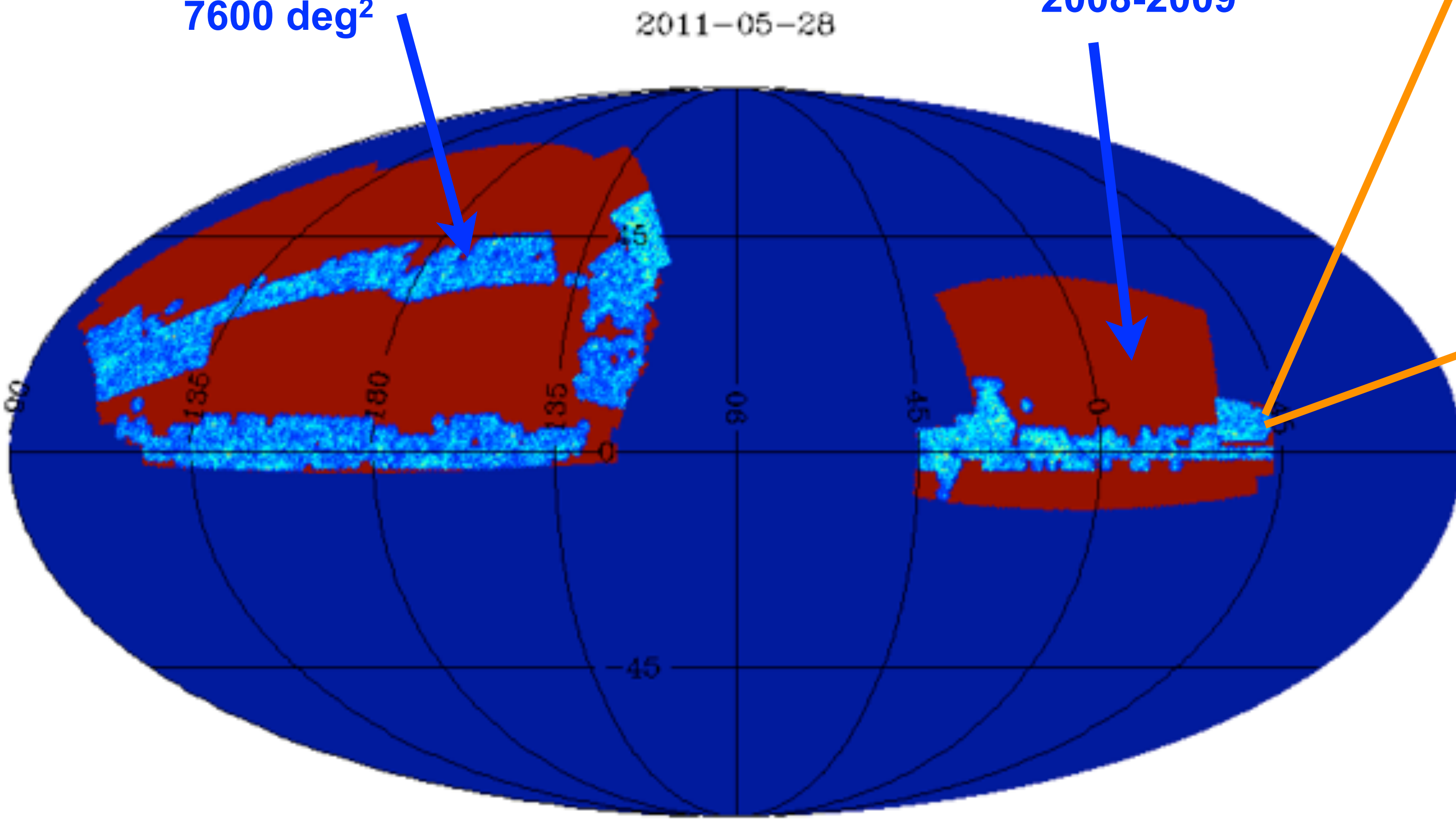


BOSS: Start with a 2-D image

All targets selected from SDSS
Requires 10,000 deg^2 footprint

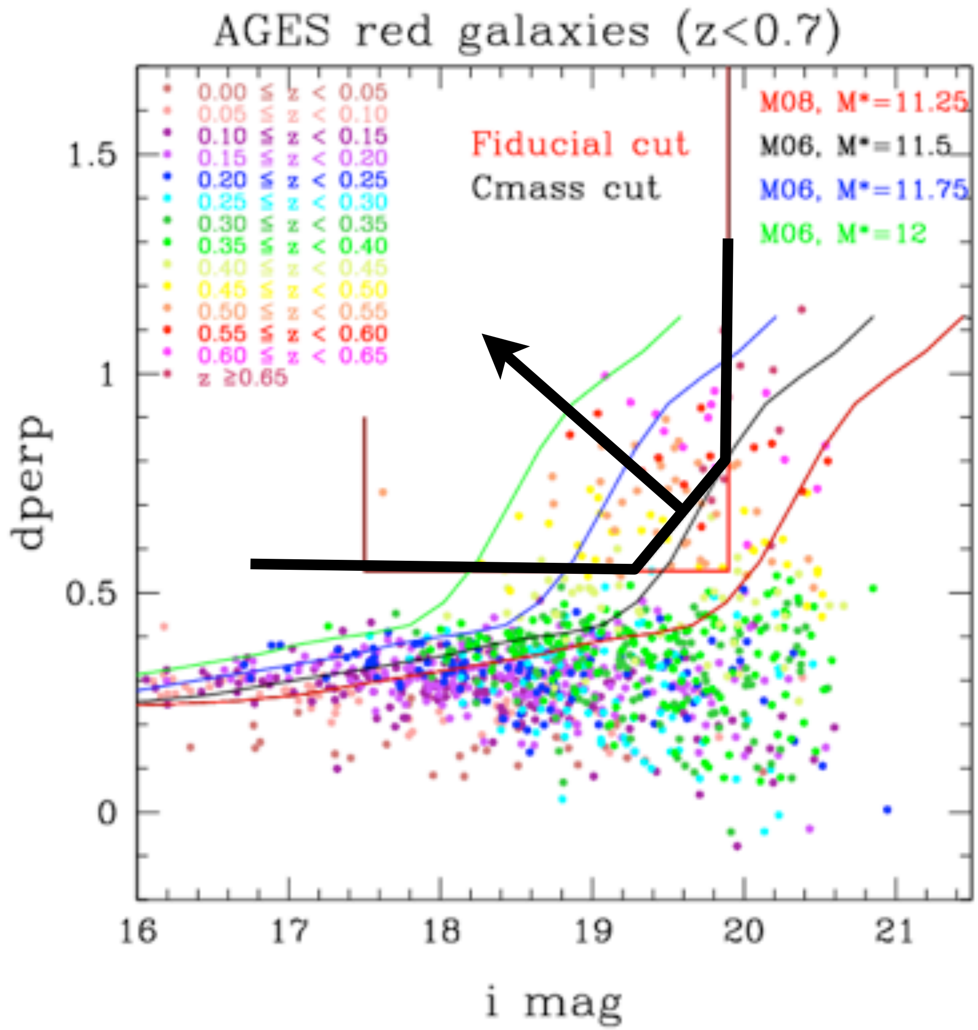
SDSS & SDSS-II imaging
7600 deg^2

BOSS imaging
...add 3100 deg^2 in 2008-2009



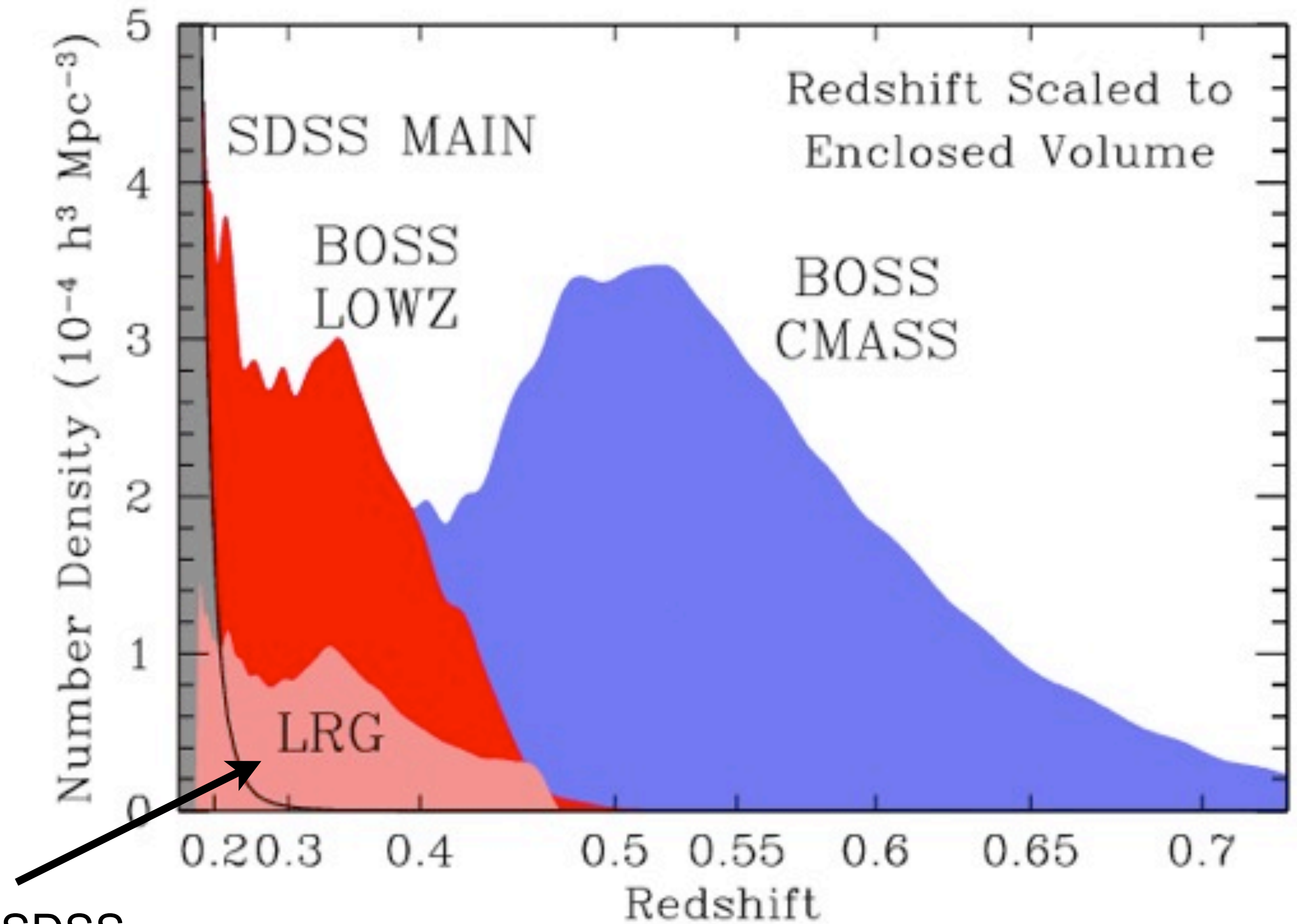
BOSS target sample: "CMASS" galaxies

Most luminous galaxies, in largest dark matter halos
Selected as ~constant stellar mass sample at 0.4 < z < 0.7



BOSS target sample: “CMASS” galaxies

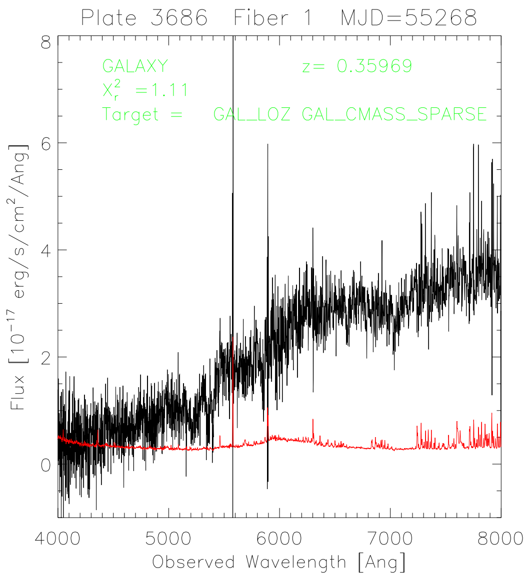
Attempt at ~constant volume density of targets for BAO



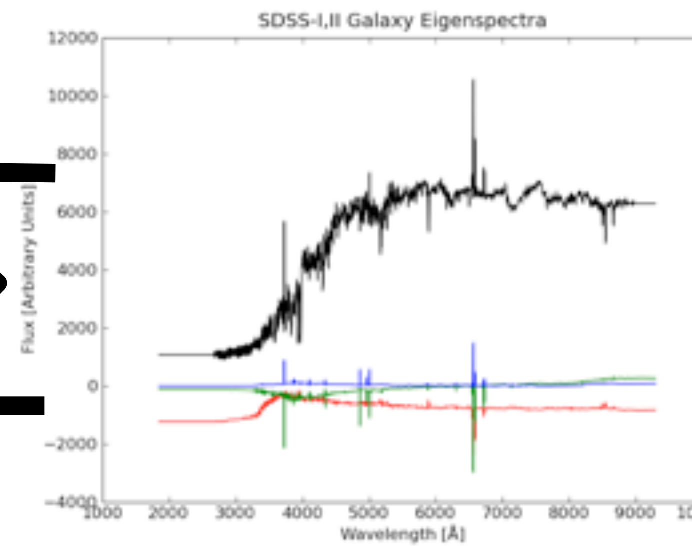
Original SDSS

BOSS: Start with a 2-D image ... then take a spectrum → redshift distance

Optical fiber collects all photons within 2-arcsec



= $\sum$



Hypothesis test:

Search all possible objects + redshifts

("Computers are cheap")

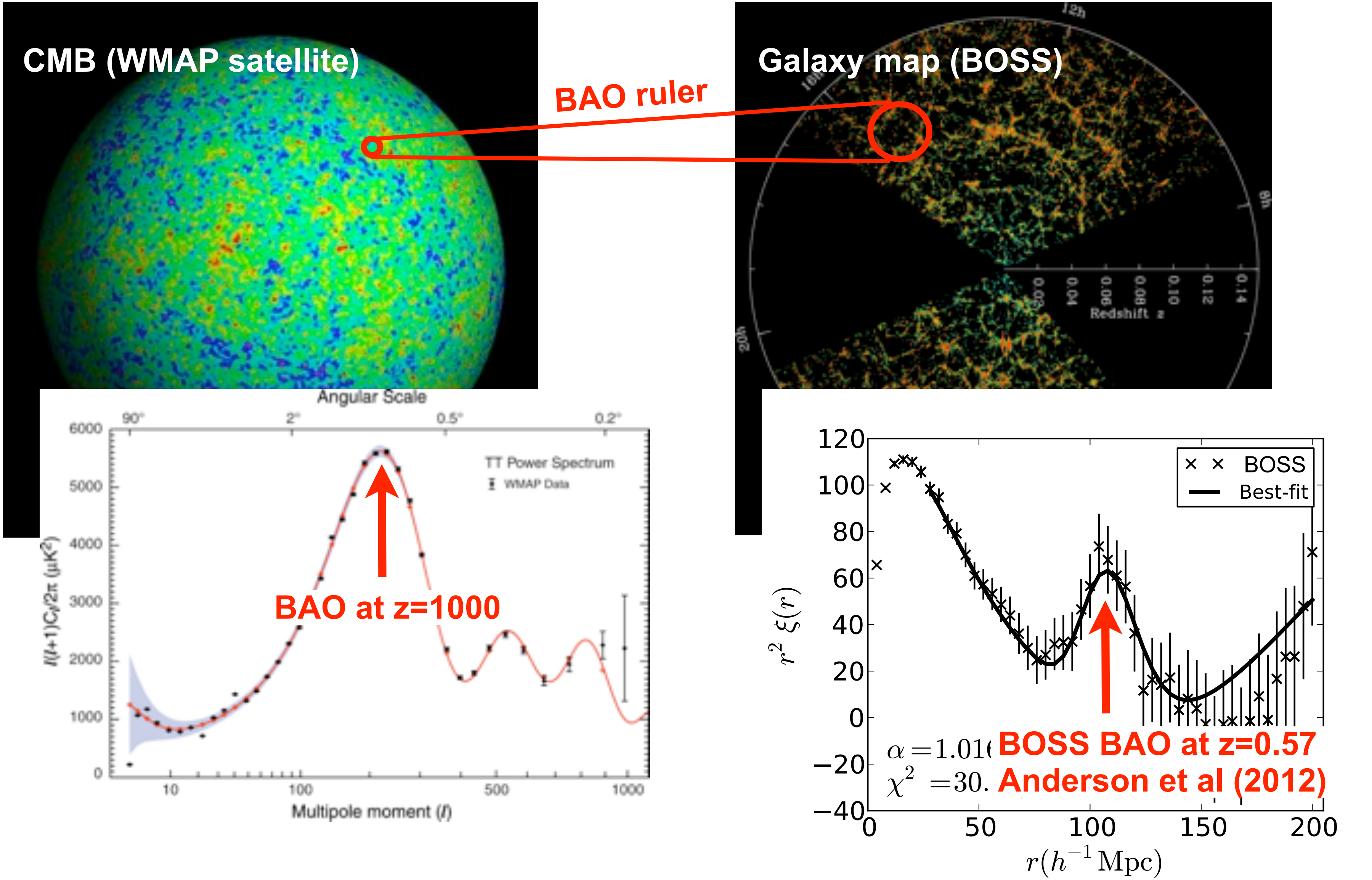
BOSS spectroscopic survey 68% complete

June 2011 - 33% complete
June 2012 - 68% complete
June 2014 - survey completion

From press release for BOSS Data Release, July 2012 http://www.interactions.org/cms/?pid=1032110

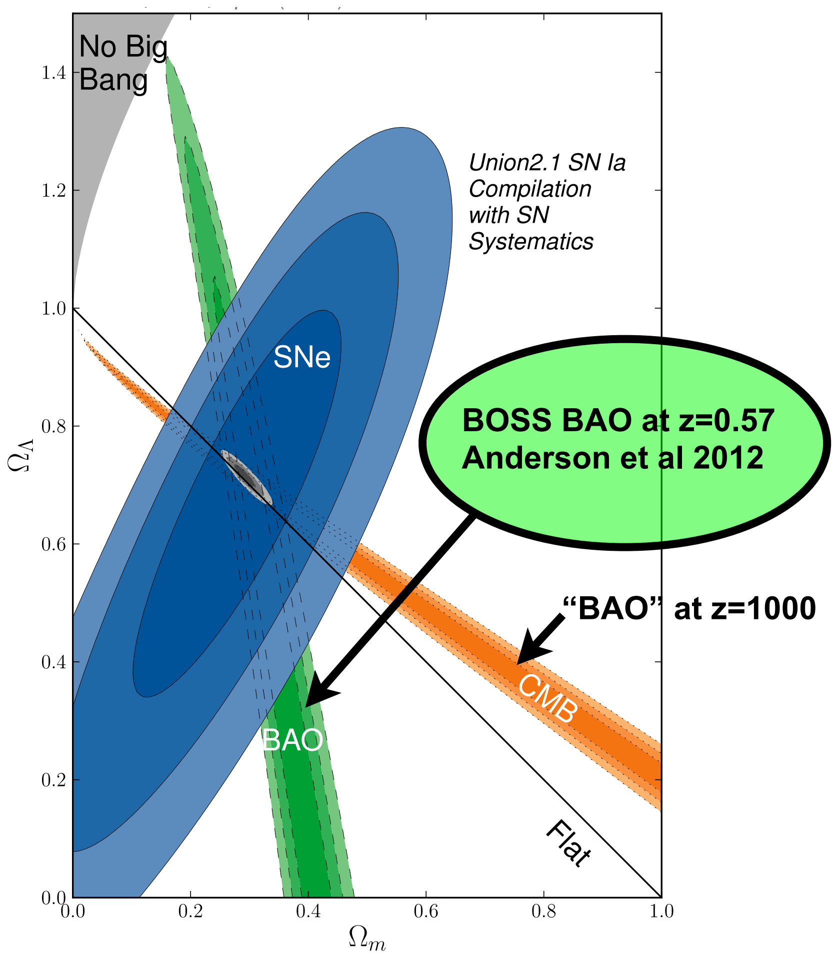
BOSS BAO first results supersede all previous

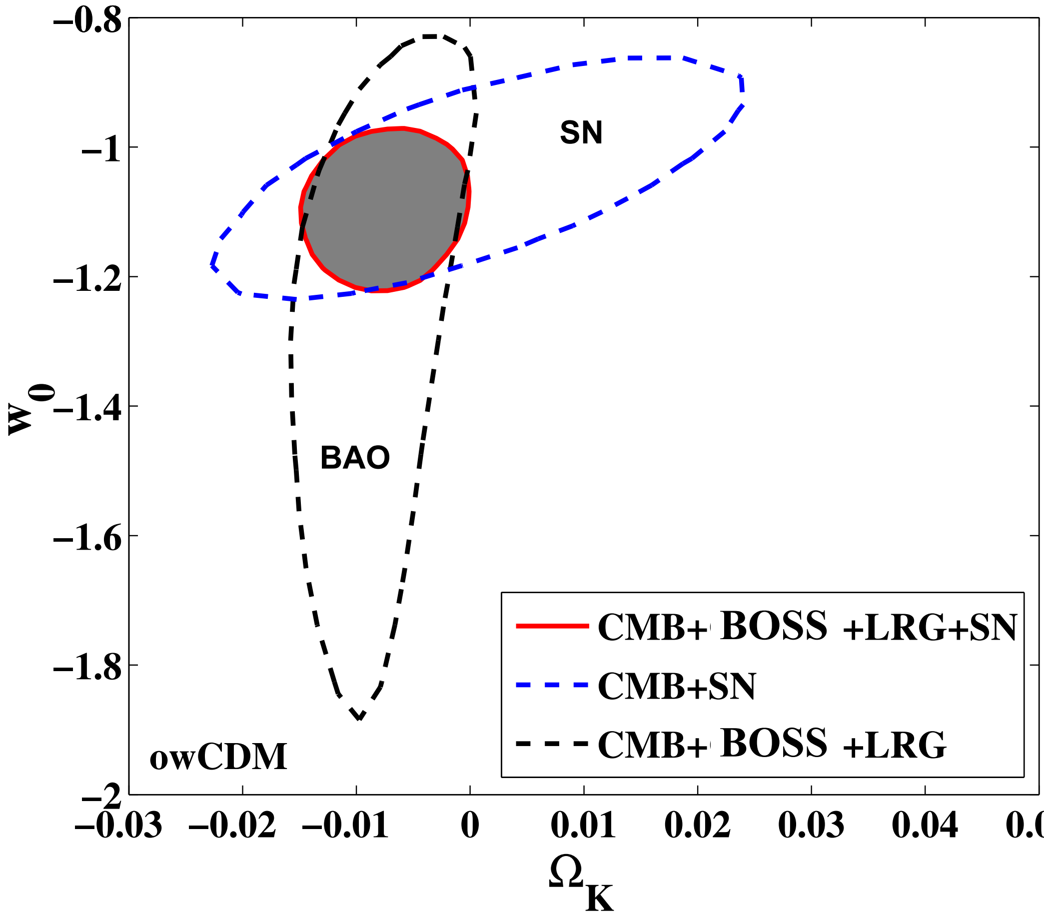
1.7% precision distance measure from first 1/3 of data, March 2012



BOSS BAO first results add significant constraints

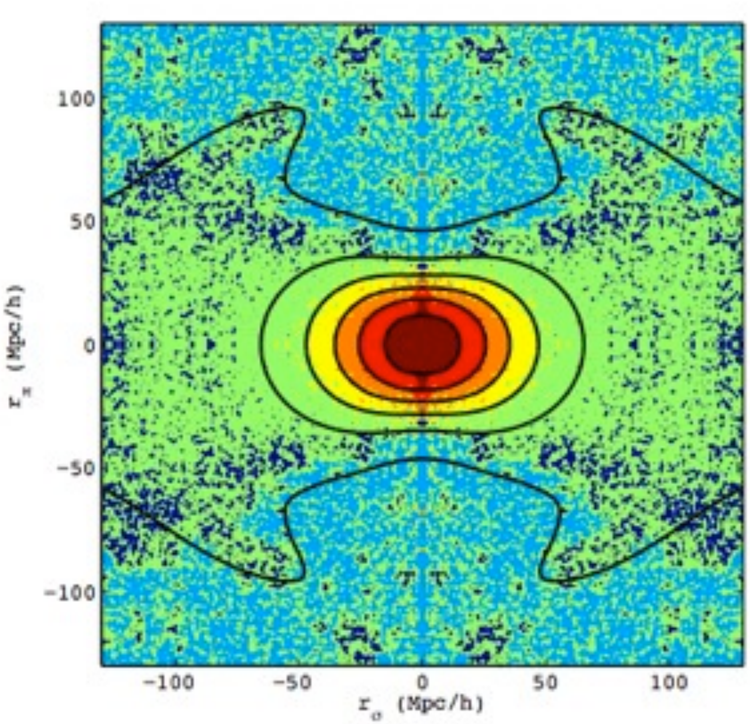
Anderson et al, 2012





BOSS RSD first results supersede all previous

Dark energy vs. gravity tested from redshift space distortions (RSD)



Correlation function in 2 dimensions: would be circular if no gravitational growth

First results from Reid et al (2012)

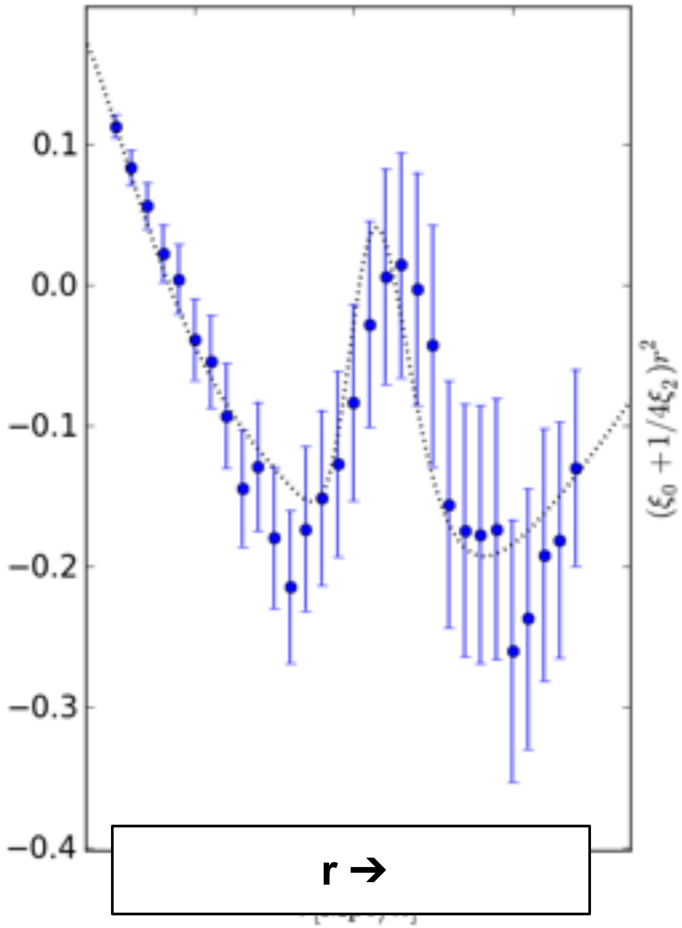
Ang diam distance 2190 +/- 61 Mpc

Hubble param 92.4 $^{+4.5}_{-4.0}$ km/s/Mpc

Growth rate dσ8 / dlna = 0.43 $^{+0.069}_{-0.063}$

BOSS BAO at z>2 coming soon!

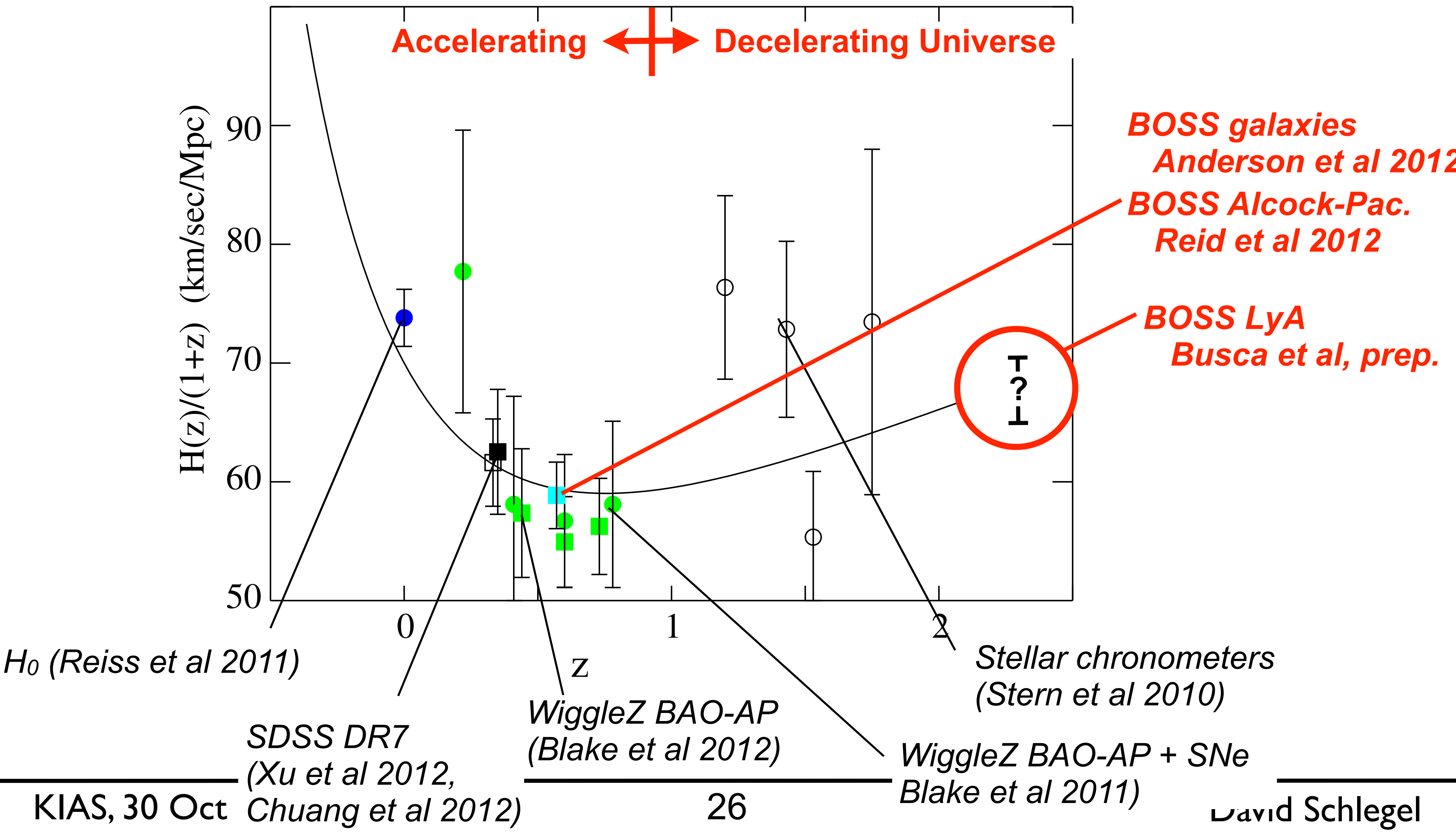
Blinded analysis of first 1/3 of data
All data went public July 31, 2012
3% distance measure at z=2.4, in prep. for Nov 13, 2012
... but someone could beat us with our own data :)



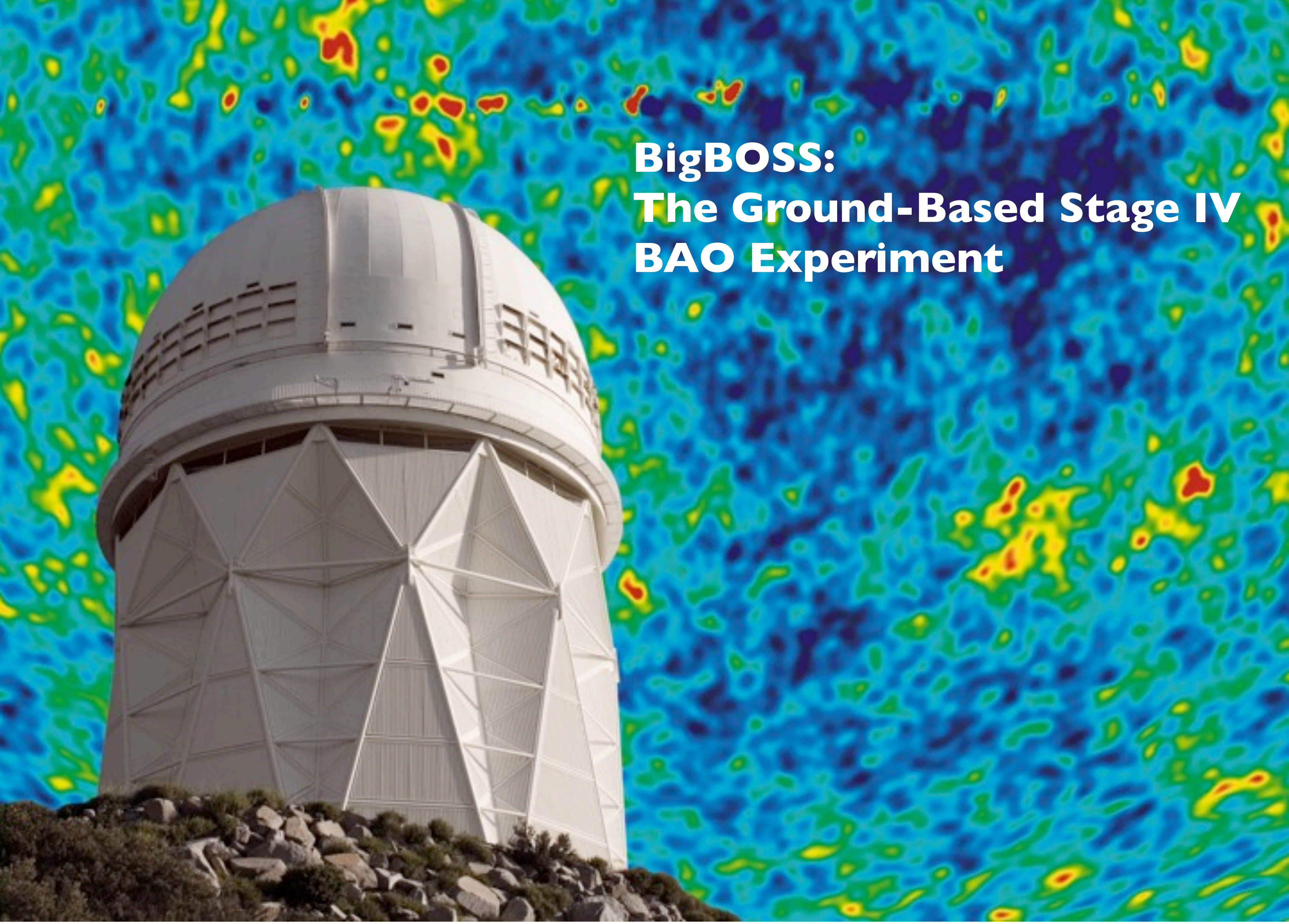
Busca et al (2012) in prep
Slosar et al (2012) in prep

Era of deceleration measured by BOSS Ly-alpha

First results to decisively map when the universe was decelerating
No other experiment measuring in this regime



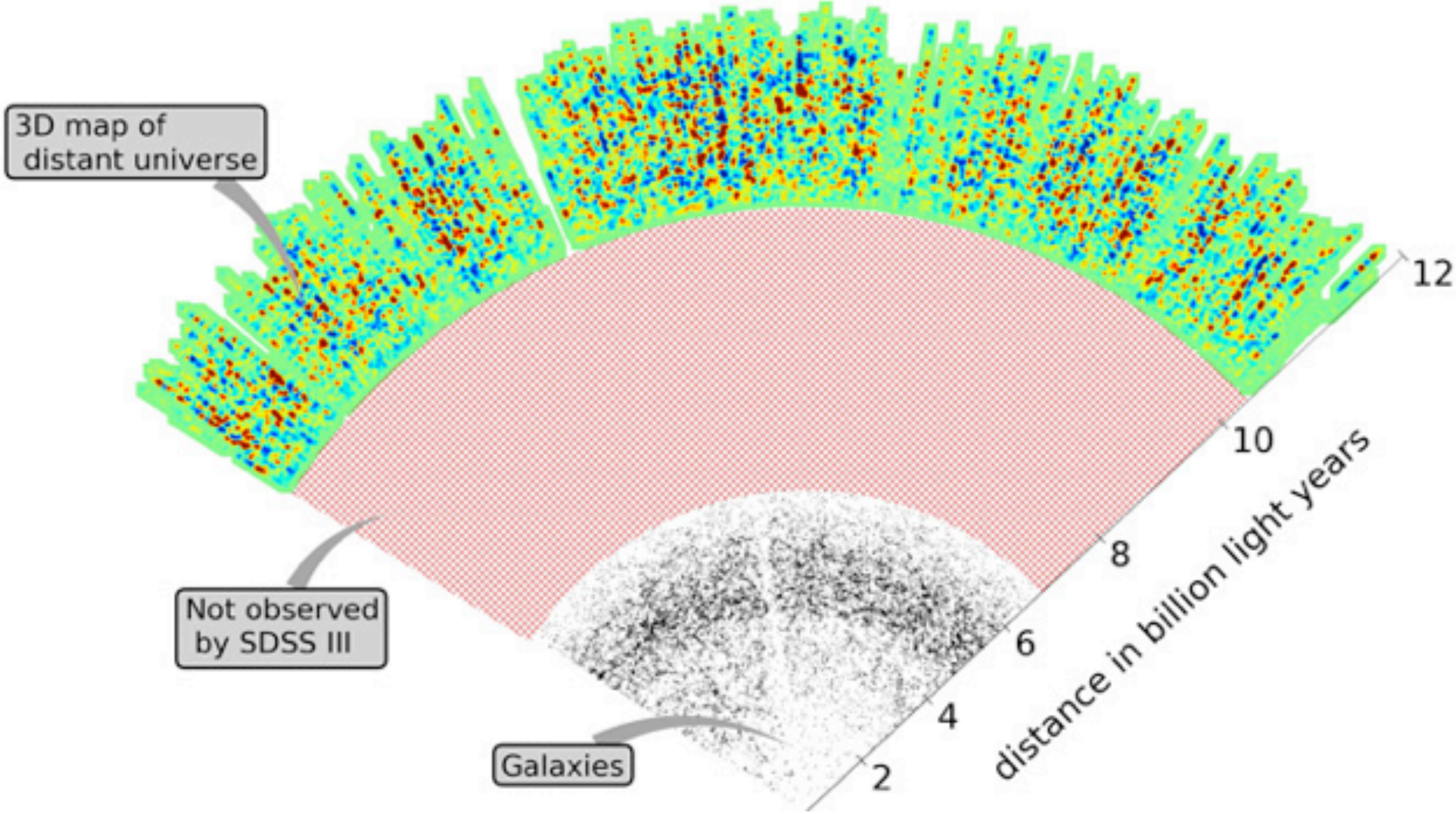
BigBOSS:
The Ground-Based Stage IV BAO Experiment



What is BigBOSS?

The largest spectroscopic survey for dark energy

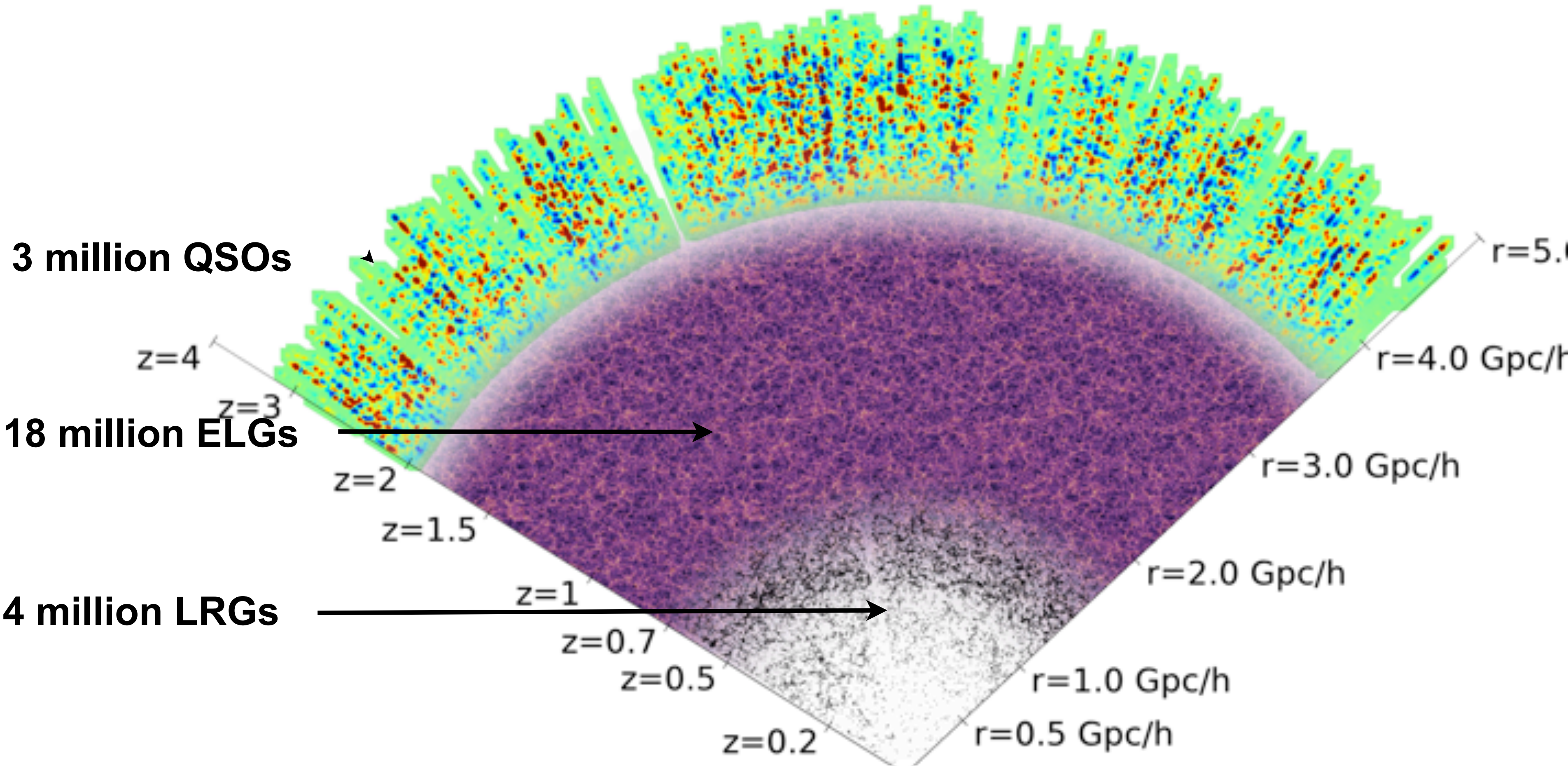
SDSS ~2h^{-3}Gpc^3 ⇨ BOSS ~6h^{-3}Gpc^3



What is BigBOSS?

The largest spectroscopic survey for dark energy

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



BigBOSS began as a search for a suitable telescope in 2009

Name	Site	Notes and Exclusions	M1 f/#	M1 Diam. (m)	f/#	f (m)	Suitable for BigBOSS corrector?
Vista	Cerro Paranal, Chile	ESO Committed	f/1.0	4.1	1	4.1	no
Starfire	Kirtland AFB, New Mexico	Military	f/1.5	3.5	1.5	5.25	no
SOAR	Cerro Pachon, Chile		f/1.7	4.2	1.7	7.14	no
WIYN	Kitt Peak, Arizona		f/1.8	3.5	1.8	6.3	no
ARC	Apache Point, New Mexico		f/1.8	3.5	1.8	6.3	no
Discovery Channel	Lowell Obs, Arizona		f/1.9	4.2	1.9	7.98	marginal, with 1.5m C1
Galileo TNG	La Palma, Canary Islands, Spain		f/2.2	3.6	2.2	7.92	marginal
NTT ESO	Cerro La Silla, Chile	ESO Committed	f/2.2	3.5	2.2	7.7	yes
William Herschel	La Palma, Canary Islands, Spain		f/2.5	4.2	2.5	10.5	marginal
Victor Blanco	Cerro Tololo, Chile	Twin to Mayall	f/2.8	4	2.8	11.2	yes
Mayall	Kitt Peak, Arizona	Twin to Blanco	f/2.8	3.8	2.8	10.64	yes
AEOS	Maui, Hawaii	Military	f/3.0	3.7	3	11.1	yes
ESO 3.6m	Cerro La Silla, Chile	ESO Committed	f/3.0	3.6	3	10.8	yes
AAT	Coonabarabran, NSW, Australia	2 arcsec seeing	f/3.2	3.9	3.22	12.558	yes
Hale	Palomar Mountain, California		f/3.3	5.1	3.3	16.83	no, massive corrector
MPI-CAHA	Calar Alto, Spain	Poor seeing	f/3.5	3.5	3.5	12.25	yes
CFHT	Mauna Kea, Hawaii	Proposed 10m	f/3.8	3.6	3.8	13.68	yes

- **Faster speed M1 = More difficult**
- **Larger M1 → larger C1. C1 diameter > 1.25m prohibitively expensive**

BigBOSS has been awarded 500 nights on the Mayall Telescope

NOAO > KPNO Home

Announcement of Opportunity for Large Science Programs Providing New Observing Capabilities for the Mayall 4m Telescope on Kitt Peak

NOAO announces an opportunity to partner with NOAO and the National Science Foundation to pursue a large science program with the Mayall 4-meter telescope on Kitt Peak and to develop a major observing capability (instrument, software, and archival plans) for the Mayall 4-meter telescope of the Kitt Peak National Observatory for the purpose of enabling large, high impact science programs and improving the capabilities provided as part of the U.S. System of ground-based optical and near-IR telescopes. Projects that use a diverse range of observing requirements (e.g. time of year, lunar phase, etc.) are encouraged. The dual goals of the large science program, as discussed in a recent edition of NOAO Currents are to enable frontier science and to improve the U.S. system of ground-based ØIR facilities. Although

BigBOSS collaboration, R&D phase

- Brookhaven National Laboratory
- Ewha Womans University, Korea
- Fermi National Accelerator Laboratory
- French Participation Group
  - APC, IAP- Paris; CPP, CPT, LAP Marseille; CEA, IRFU – Saclay
- Johns Hopkins University
- Lawrence Berkeley National Laboratory
- National Optical Astronomy Observatory
- New York University
- The Ohio State University
- Shanghai Astronomical Observatory
- SLAC National Accelerator Laboratory
- Spanish Participation Group
  - IAA, Granada; IAC, Tenerife; ICC, Barcelona; IFT, Madrid; U. Valencia
- UK Participation Group
  - Durham, Edinburgh, UC London, Portsmouth
- University of California, Berkeley
- University of Kansas
- University of Michigan
- University of Pittsburgh
- University of Science and Technology of China
- University of California, Santa Cruz/Lick Observatory
- University of Utah
- Yale University

What is BigBOSS?

Construct BigBOSS instrument:

3 deg diameter FOV prime focus corrector
5000 fiber positioner
10x3 spectrographs, 3400-10,600 Ang

Conduct BigBOSS Key Project

500 nights at Mayall 4-m
14,000 deg^2 survey
50,000,000 spectra

- *20,000,000+ galaxy redshifts*
- *3,000,000+ QSOs*

BigBOSS overview

Instrument + survey design follow requirements flow-down

LEVEL 1
SCIENTIFIC REQUIREMENTS

- Measure the distance scale error σ_R/R to < 1% for $0.5 < z < 3.0$
  (in 6 bins with $\Delta\ln(1+z) = 0.2$)
- Measure H(z) to 1.5% up to z=2.5
  (in 4 bins at $<z> = 0.7, 1.1, 1.5, 2.5$)
- Constrain growth, $\sigma_8(z)$ f(z), with <2% relative error
  ($\Delta z = 0.1$ bins, $k_{max} = 0.2$, for $0.5 < z < 1.5$)
- Measure galaxy power spectrum to < 1% up to z=1.5
  ($\Delta k = 0.02$ Mpc/h bins, $k_{max} = 0.3$)

ADDITIONAL SCIENTIFIC GOALS

- Inflation: constrain spectral index and its running to < 1%
- Measure the sum of neutrino masses $\Sigma\, m_\nu$ with $\sigma < 0.020$ eV

LEVEL 2
DATA SET REQUIREMENTS

- Survey Area: 14,000 sq deg
- Redshift range:
  - LRGs $0.5 < z < 1.0$
  - ELGs $0.5 < z < 1.6$
  - Tracer QSOs $0.5 < z < 3.5$
  - Ly-α QSOs $2.2 < z < 3.5$
- Galaxy *dN/dV* > $1\mathrm{x}10^{-4}$ $(h/\mathrm{Mpc})^3$
- Number of redshifts: 20M
- Redshift accuracy:
  - $\sigma_z < 0.001(1+z)$ rms
  - < 5% catastrophic failures
  - resolve OII doublet for $0.76 < z < 1.6$

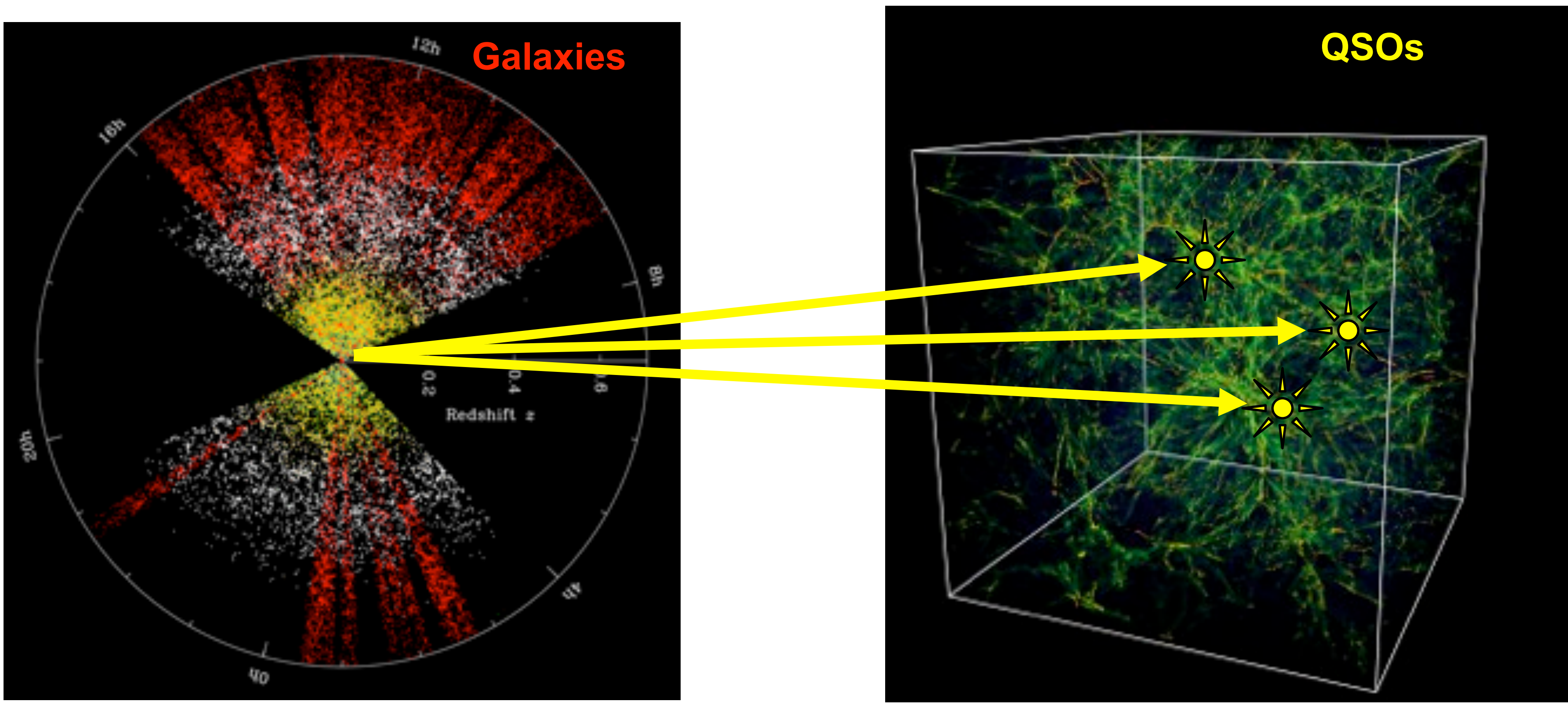
LEVEL 3
INSTRUMENT REQUIREMENTS

- Operational Constraints
  - < 500 nights
  - Instrument compatible with Mayall telescope
  - Preserve use of f/8 secondary
  - Typical seeing, weather for site used in forecasts
- Field of View: 3 deg diameter
- Number of Fibers: 5000
- Operational overheads: total < 60 s/exposure
- Spectral Range and Resolution
  - 360 nm < λ <660 nm: R > 1500
  - 620 nm < λ <840 nm: R > 3000
  - 800 nm < λ <980 nm: R > 4000
- Optical Throughput vs λ
- Fiber Positioning Error < 0.35 asec (rms, includes actuators, guiding, tracking, target astrometry)

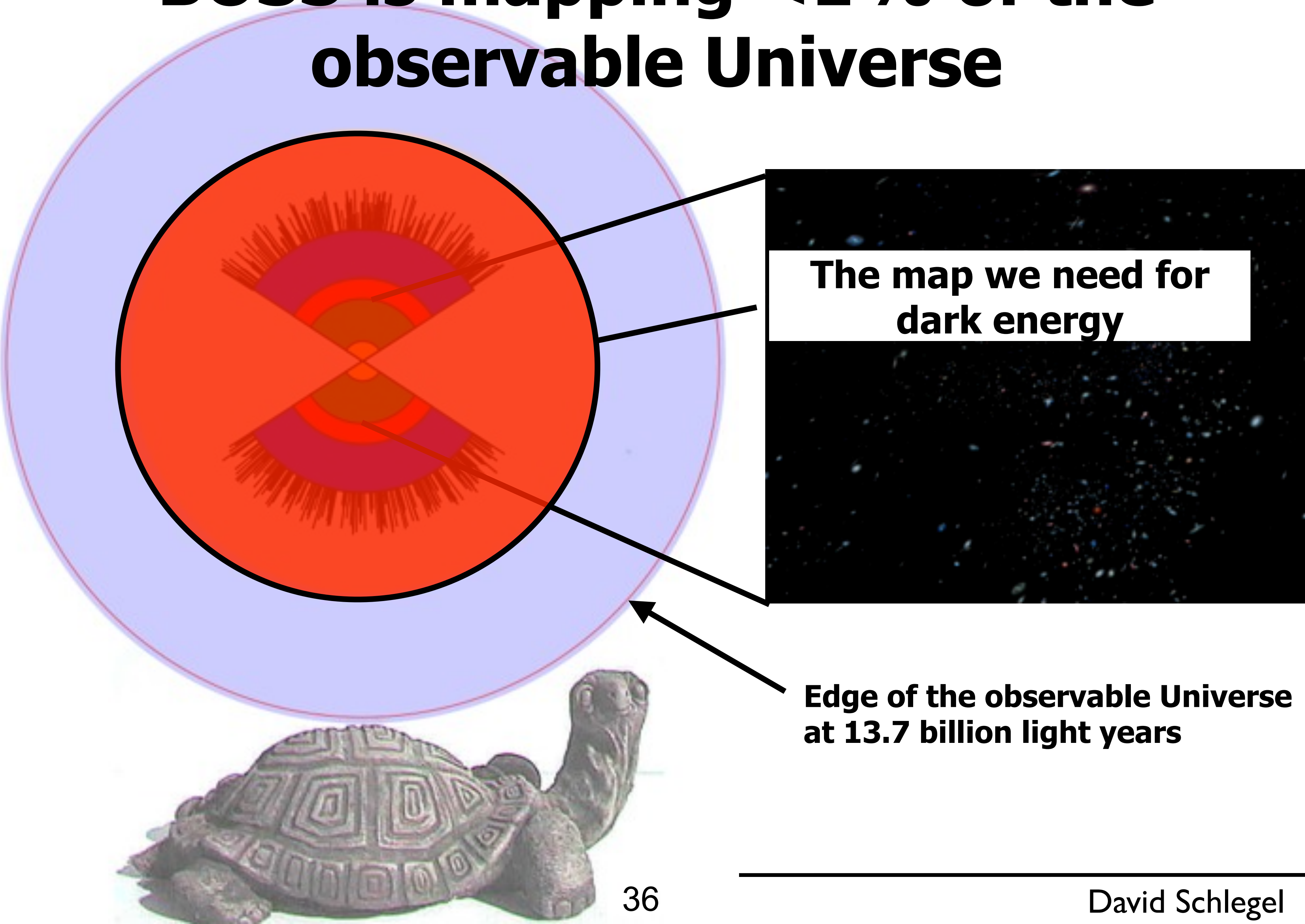
BigBOSS overview

BigBOSS designed to measures dark energy from the BAO "standard ruler"
1. Spectroscopic survey of ~20 million galaxies at $0 < z < 1.7$
2. Spectroscopic survey of ~600k QSOs at $2.2 < z < 3.5$

Definitive BAO experiment at $0 < z < 1.5$ → ***10X volume of BOSS***
Inflation probe exceeding reach of Planck satellite → ***More linear modes; full power not yet explored***



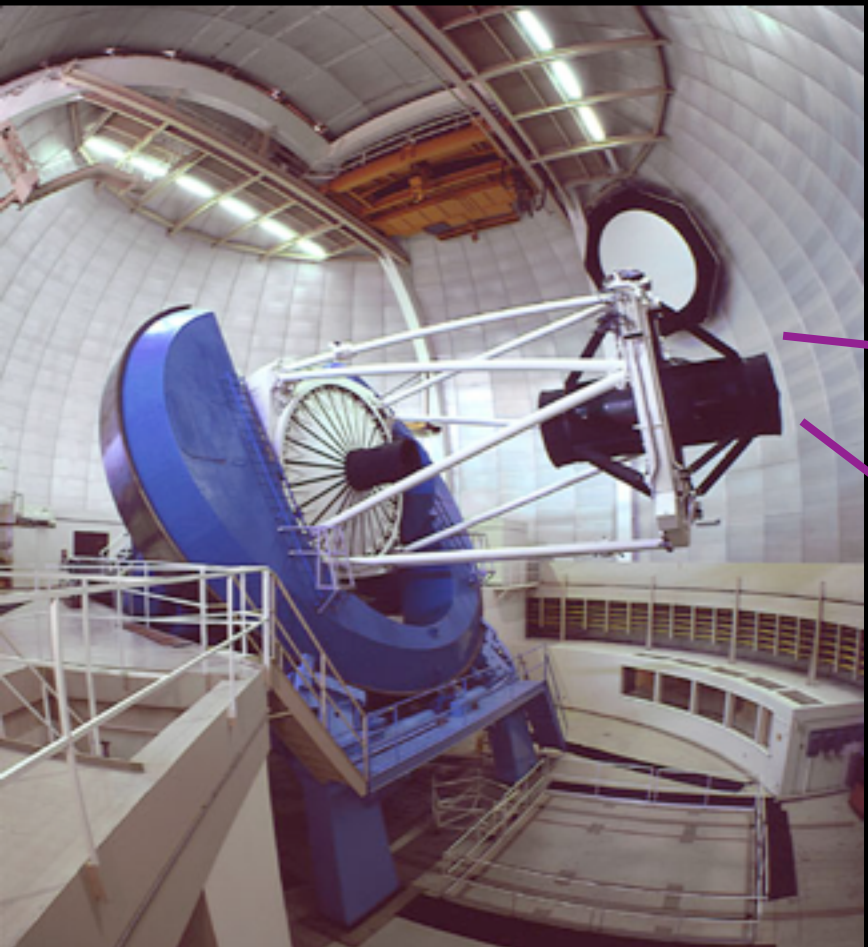
BOSS is mapping <1% of the observable Universe

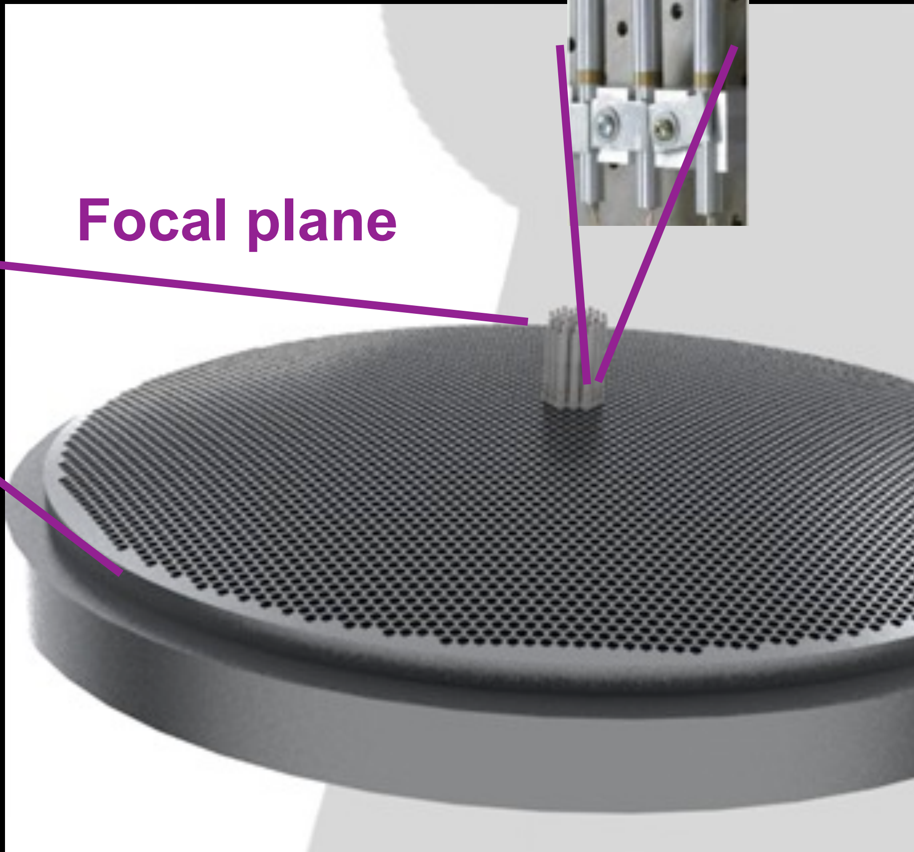


BigBOSS is the next big step in mapping the Universe

>15X more powerful than BOSS

5000 robotic positioners on a 4-m telescope

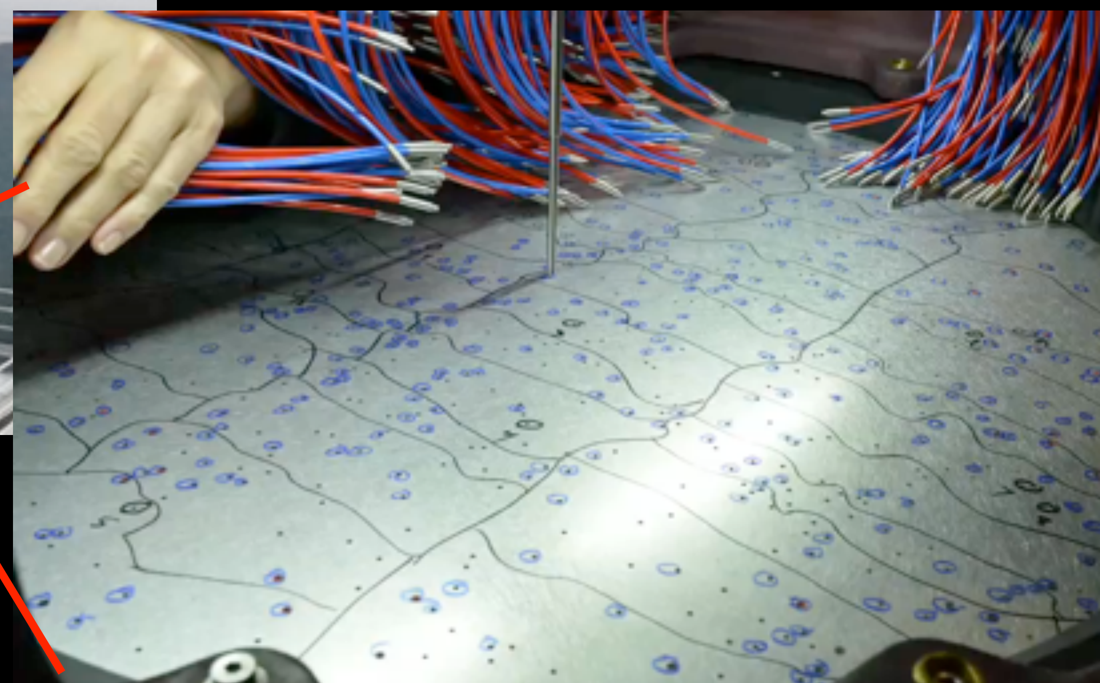




BOSS limitation using hand-plugged "plates"

Not possible to plug >2 million galaxies

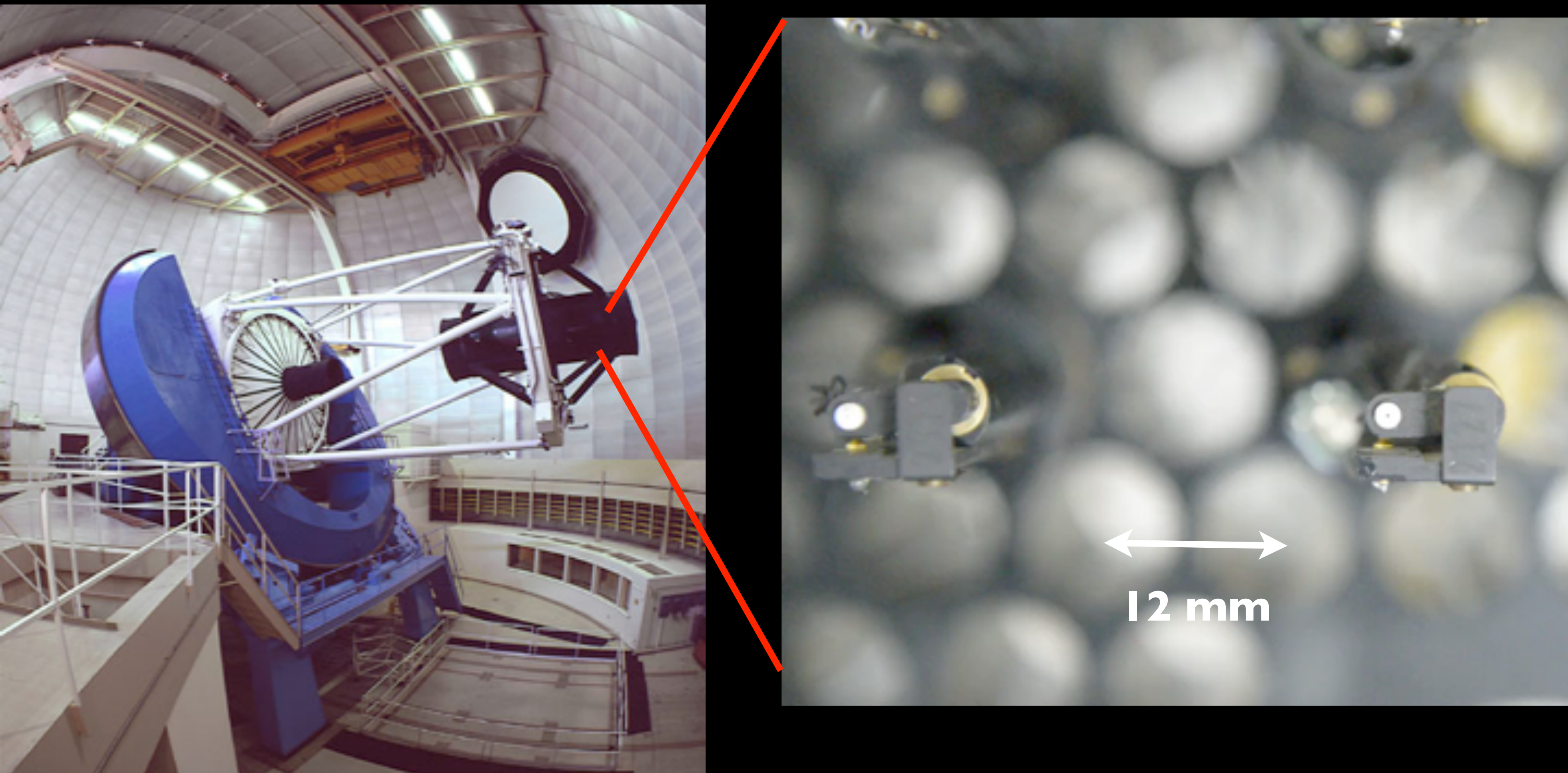
1000 fibers



BigBOSS using robotically-positioned fibers

Map of 50 million galaxies possible

5000 fibers



BigBOS

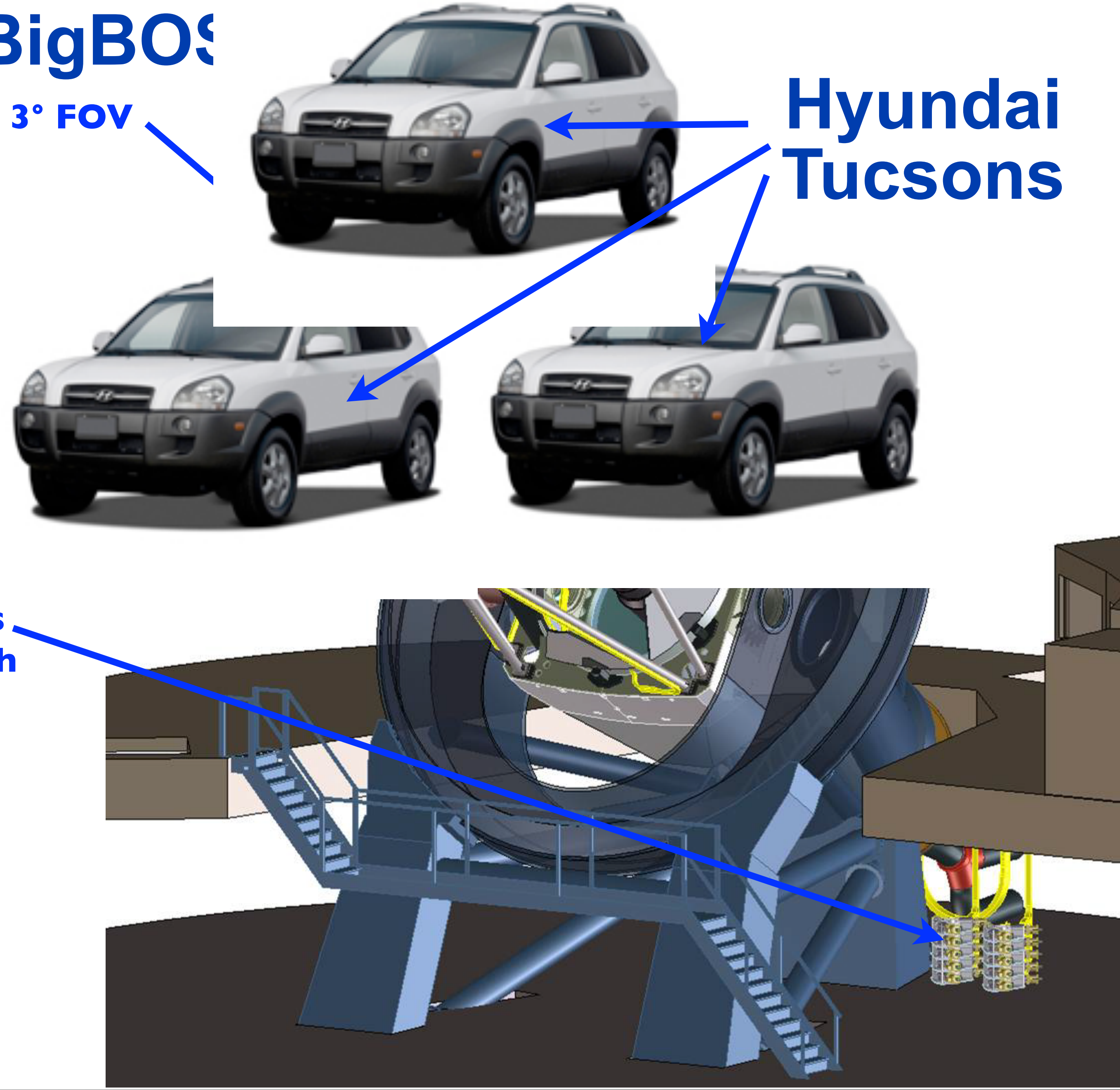
Corrector lenses, 3° FOV

5000 fiber positi
on 1.0-meter fo

5000 fibers

Fiber-view cam

10 spectrographs
X 3 channels each

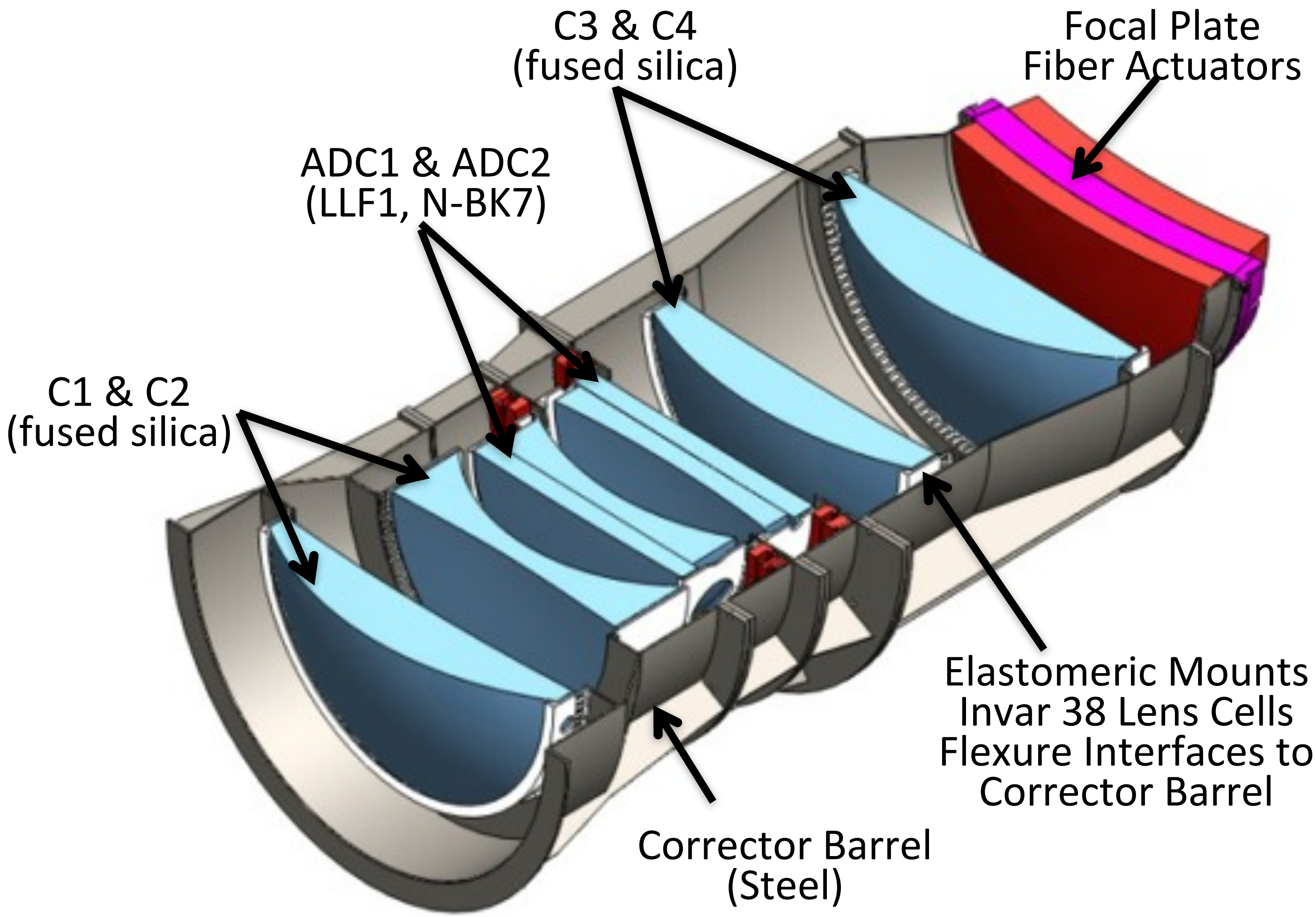


BigBOSS instrument: Corrector

New family of optical designs for 3-degree field

"Chief ray normal" design maximizes injection throughput

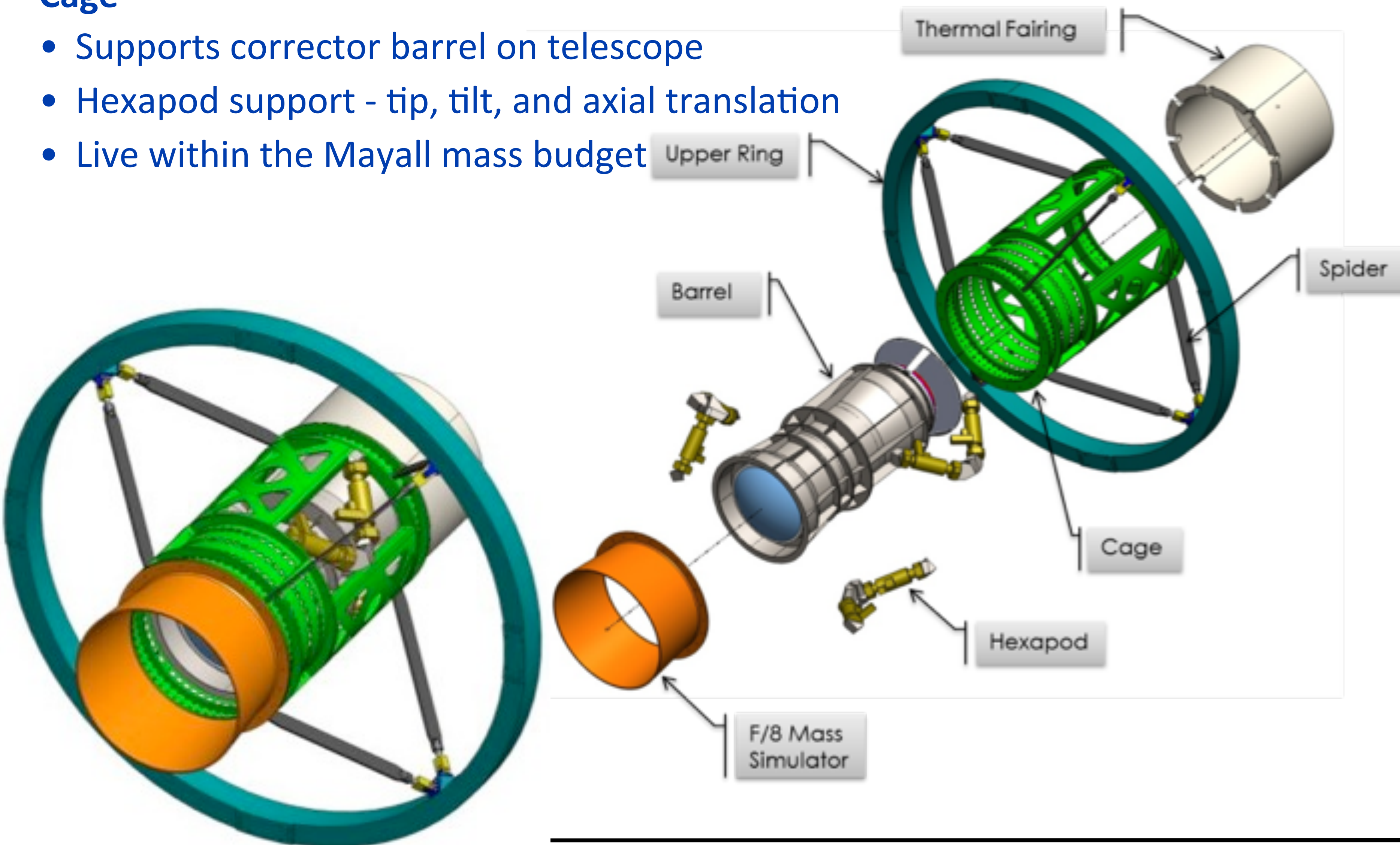
Largest lens 1.16 meter



BigBOSS instrument: Telescope top-end

Cage

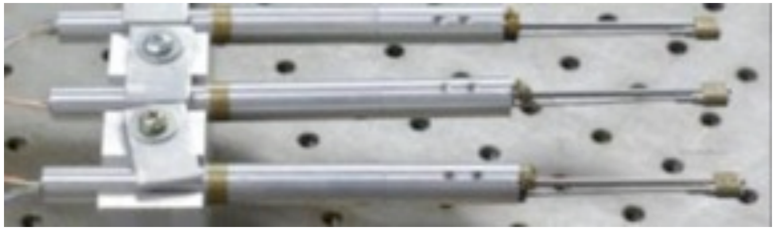
- Supports corrector barrel on telescope
- Hexapod support - tip, tilt, and axial translation
- Live within the Mayall mass budget



BigBOSS instrument: Fiber robots

R&D developed 3 robot designs
Design selection in March 2013

θ−θ USTC – LAMOST evolution



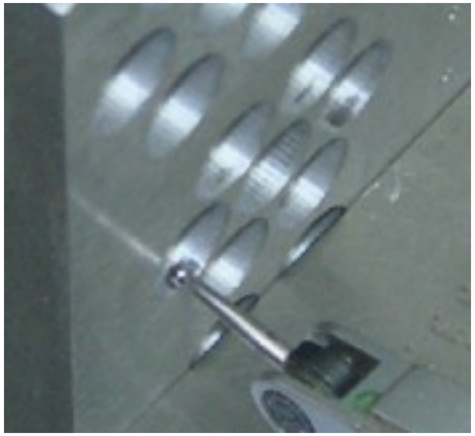
θ−θ IAA Spain – SIDE concept evolution

r−θ LBNL flexure based

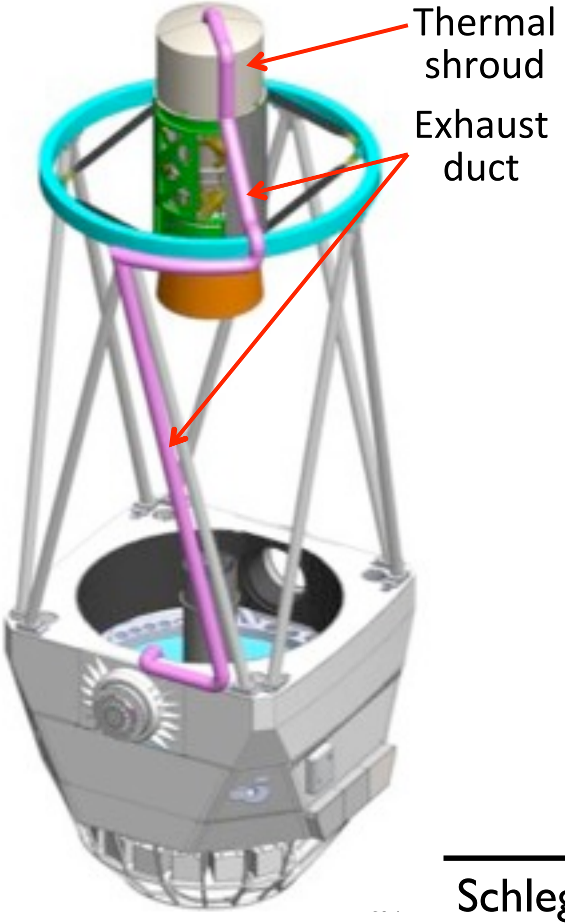
BigBOSS instrument: Focal plate

Focal plane conceptual design development.

Focal plane materials and machinability studies with industry.

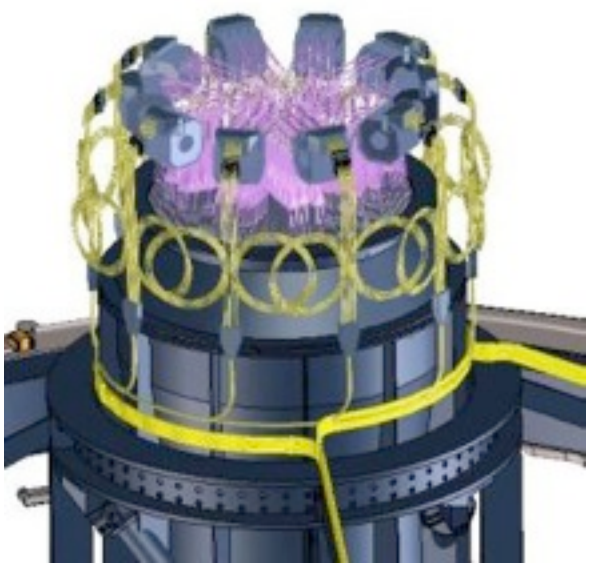


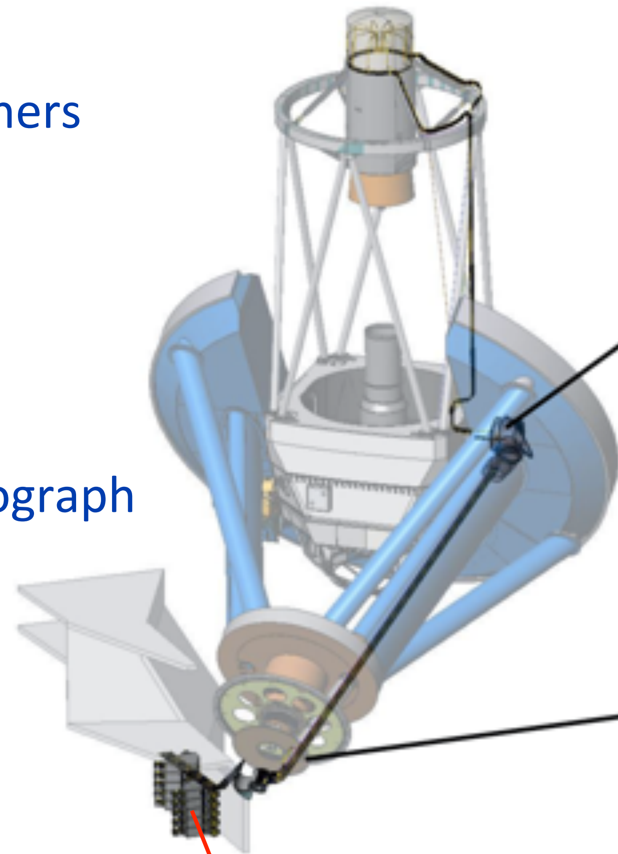
Thermal management studies to route heat from positioners and guide/focal sensors out of the air column above the primary mirror.

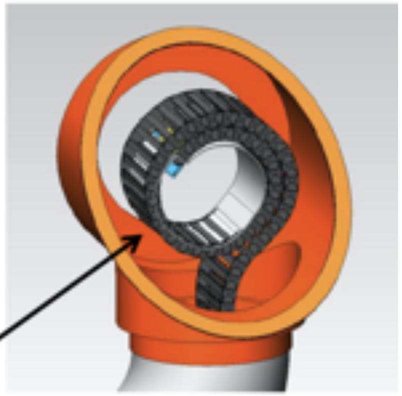


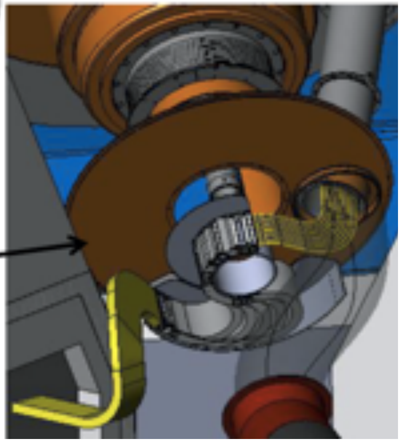
BigBOSS instrument: Fiber system

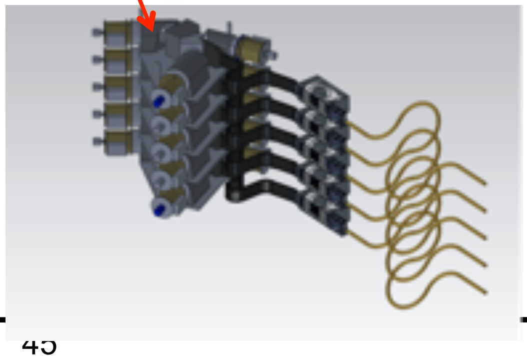
- Fiber optic bundling into cables
  - Gather single fibers from positioners
- Fiber cable routing
  - Several scenarios
  - Support fiber bundles
  - Control bending from telescope motion
- Fibers formed into a slit at spectrograph input







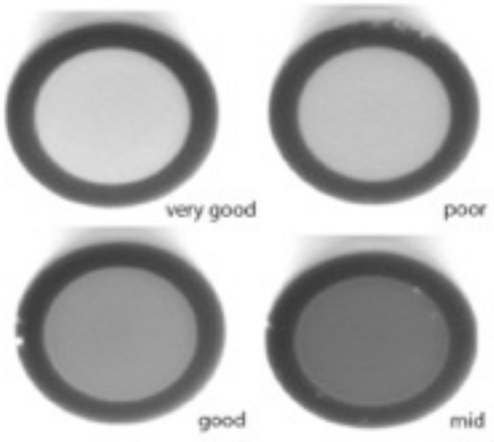




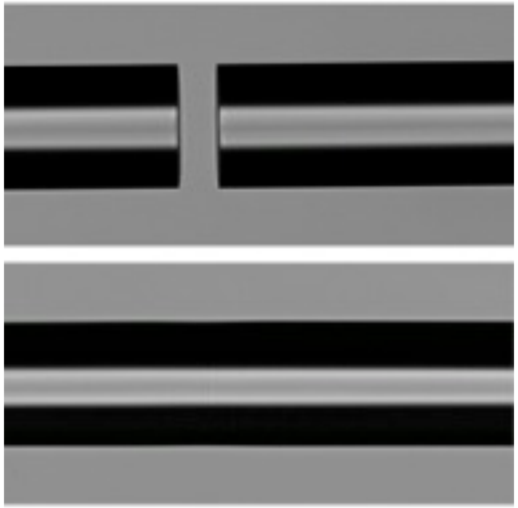
BigBOSS instrument: Fiber connections

Fusion splicing developed, avoids fiber couplers

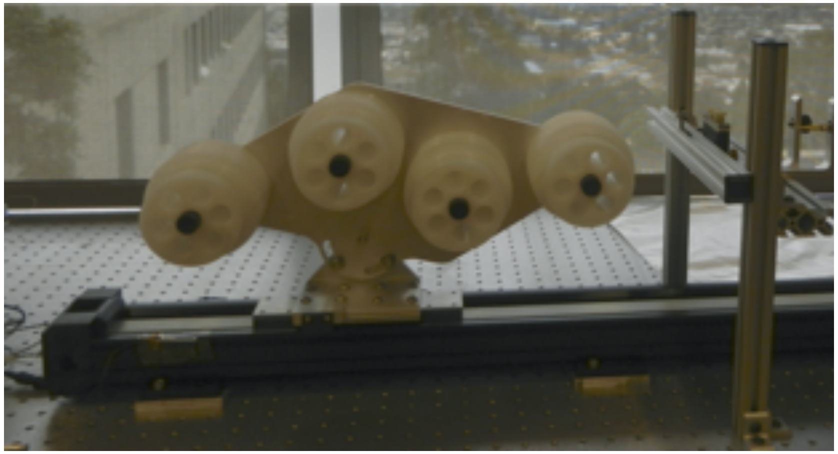
Cleaving



Fusion splicing



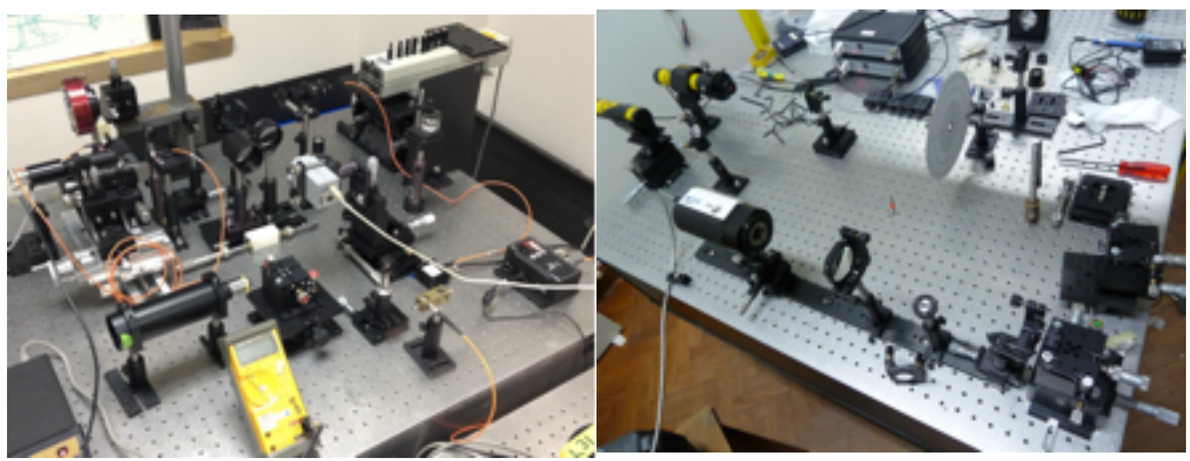
BigBOSS instrument: Fiber testing



Fiber bend

Fiber twist

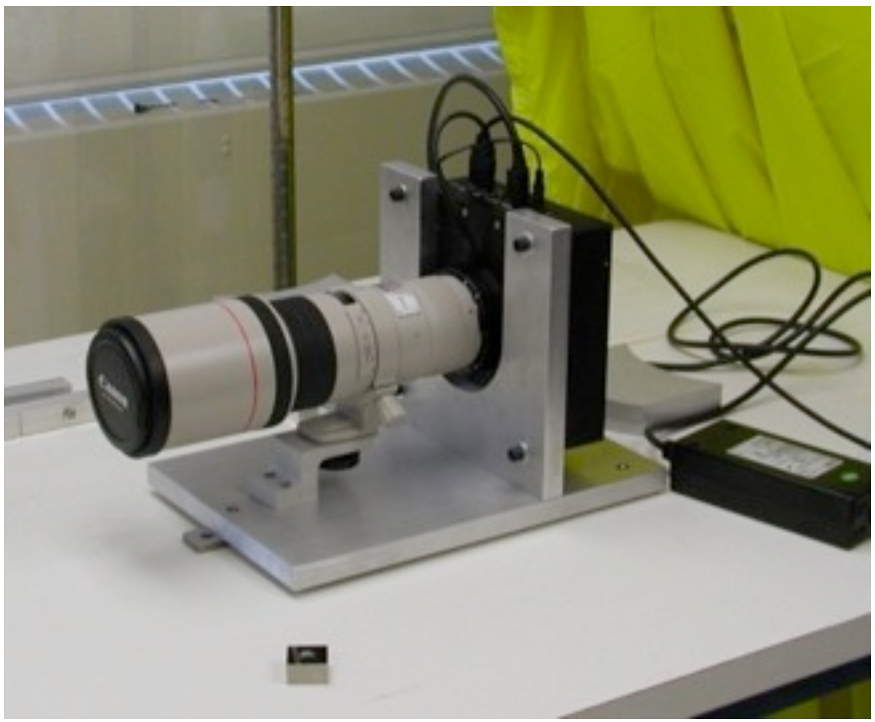
Fiber polish



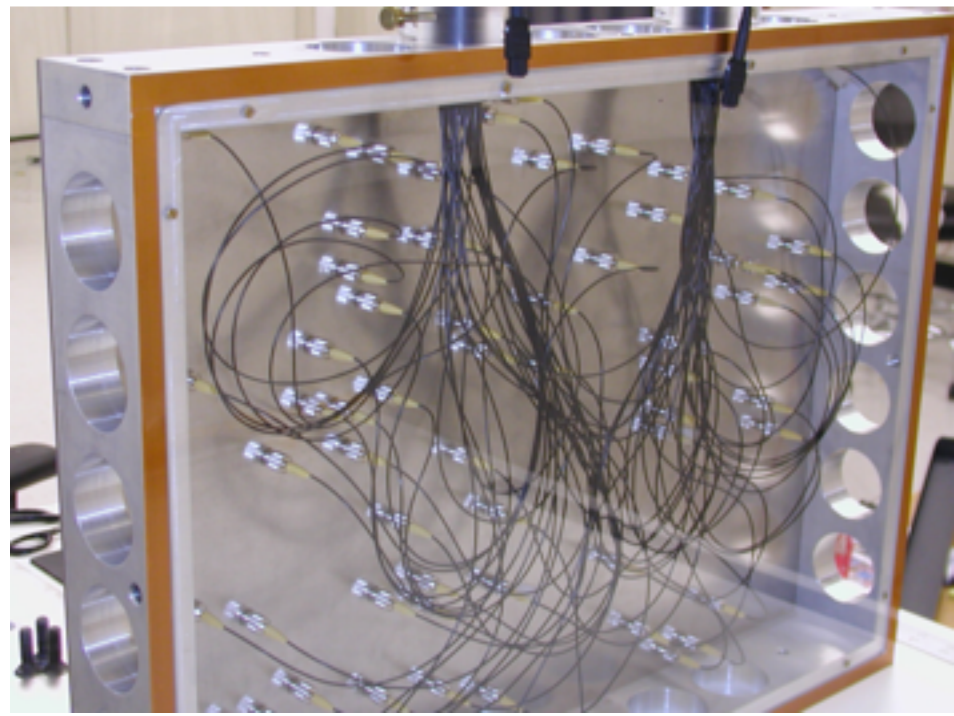
Fiber FRD Test Stands

BigBOSS instrument: Fiber-view camera

On-telescope measure of fiber positions to 5 μm (0.06")



Fiber view camera



Fiducial fiber test plate

BigBOSS instrument: Spectrographs

System throughput > 70% over most of 3600-10,000 Å

Reference spectrograph

- 3 arms, all refractive optics

— Achieve high throughput and spot size

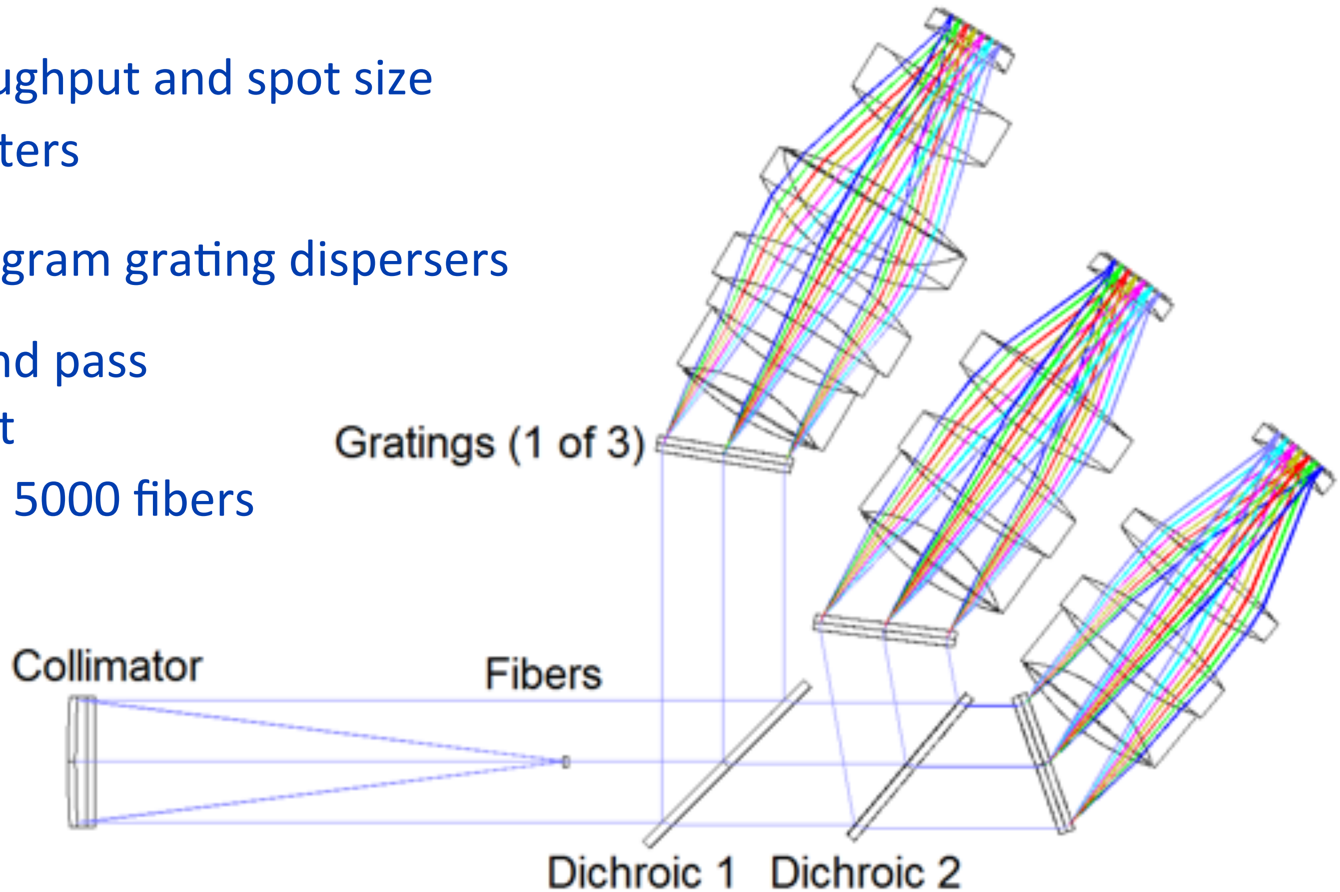
- Dichroic beam splitters

- Volume phase hologram grating dispersers

— Efficiency over band pass

— Low scattered light

- Ten copies to serve 5000 fibers

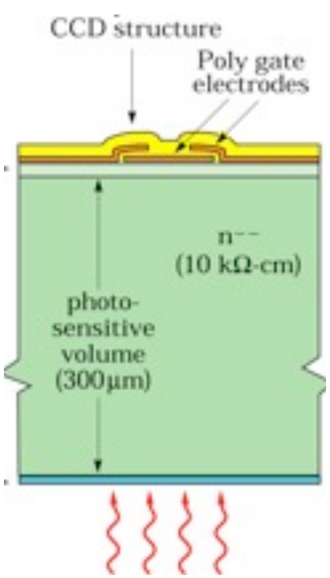


BigBOSS instrument: CCDs

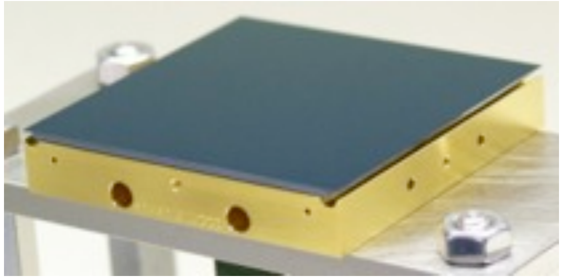
"Super-red" CCDs developed at Berkeley Lab in 2012

Longer λ → higher redshift

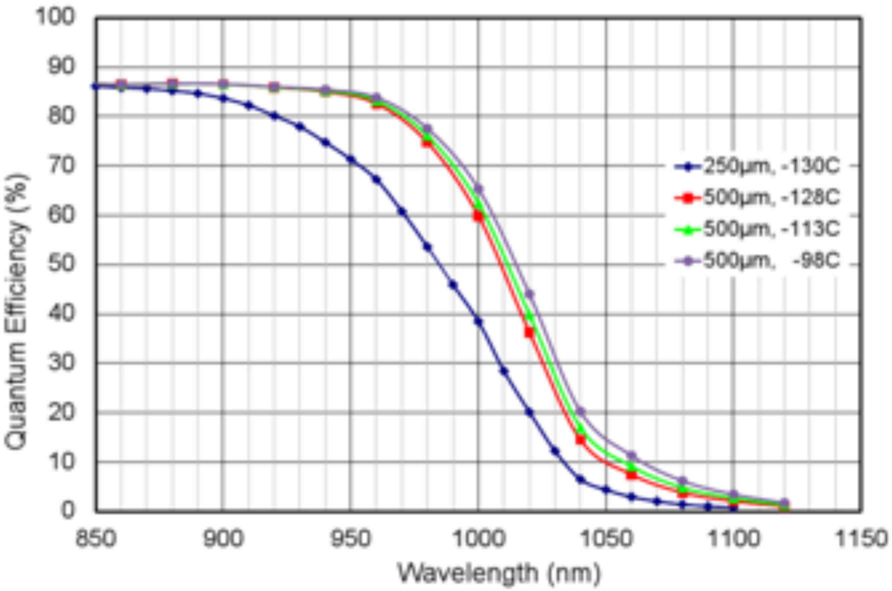
- BOSS detector technology works for BigBOSS detectors
  - LBNL fully-depleted 4k x 4k, 15µm pixel for Visible and NIR arms
  - e2v CCD231-84 4kx x 4k , 15µm pixel for Blue arm



LBNL CCD



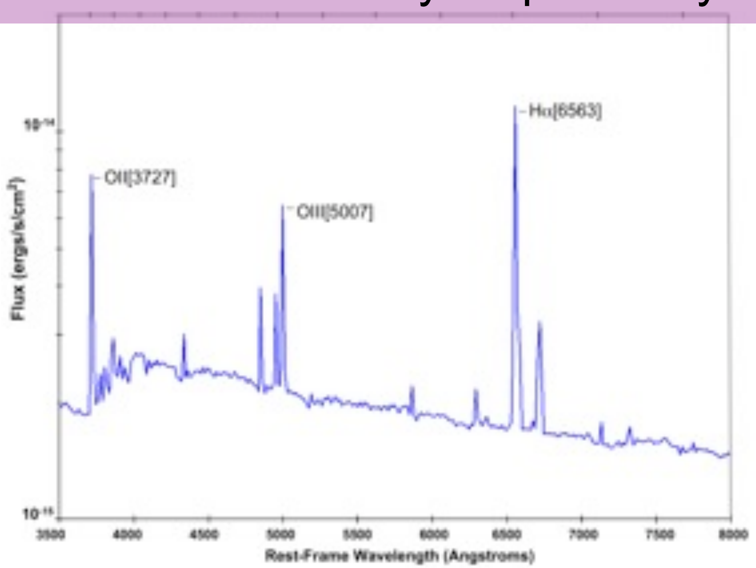
LBNL CCD quantum efficiency

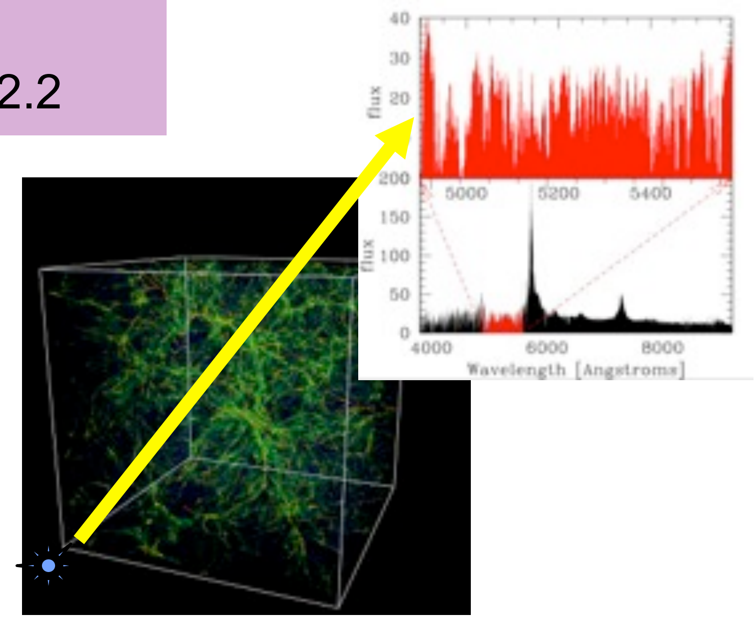


BigBOSS is the
"Easy target survey"

BigBOSS is the *"Easy target survey"*

- **Luminous Red Galaxies (LRGs):**
  - Selected to z<1
  - Efficient BAO tracers due to large bias
- **Emission-line galaxies (ELGs):**
  - Selected 0.7<z<1.7 when the Universe was forming stars
  - Redshifts from [O II], [O III] emission lines, R~5000
- **QSOs:**
  - Target ***all*** of them!
  - 3-D density map from Ly-alpha forest z>2.2





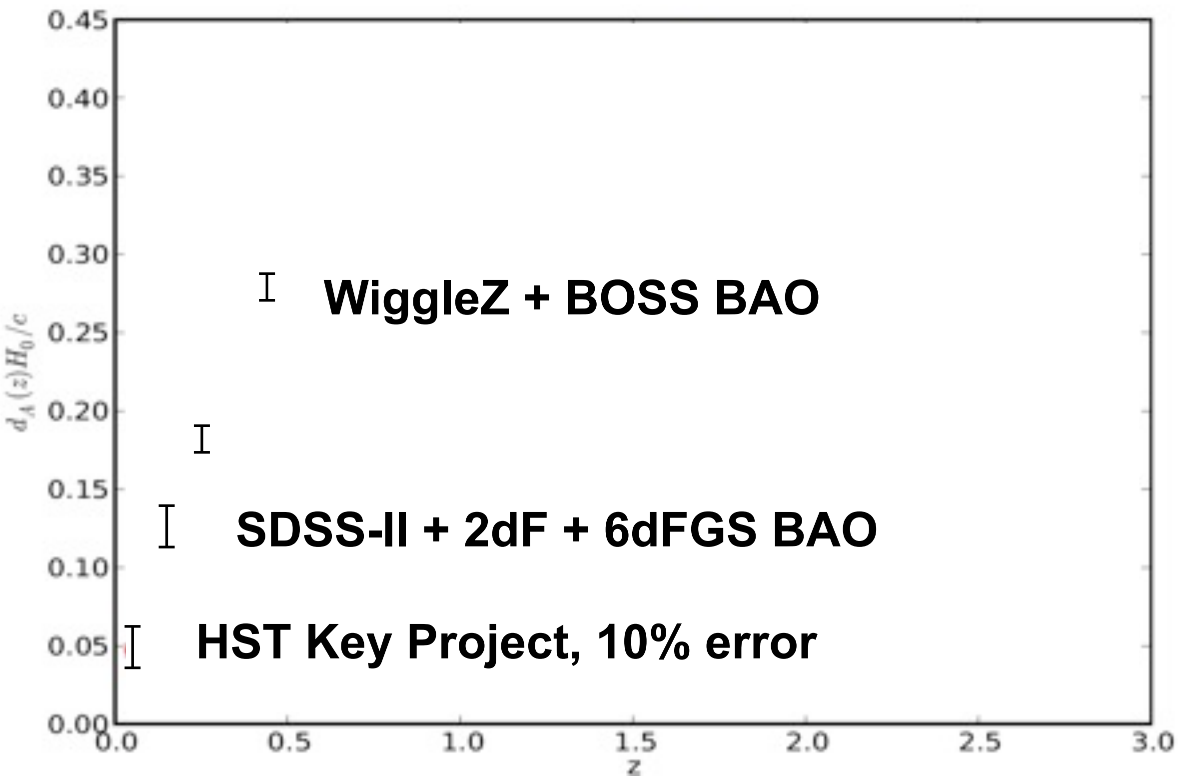
BigBOSS dark energy forecasts

BAO distances spanning z=0→3

35 measurements at 1% precision!

Precision gravity measures from RSD

Stage III BAO "Hubble diagram"



BigBOSS dark energy forecasts

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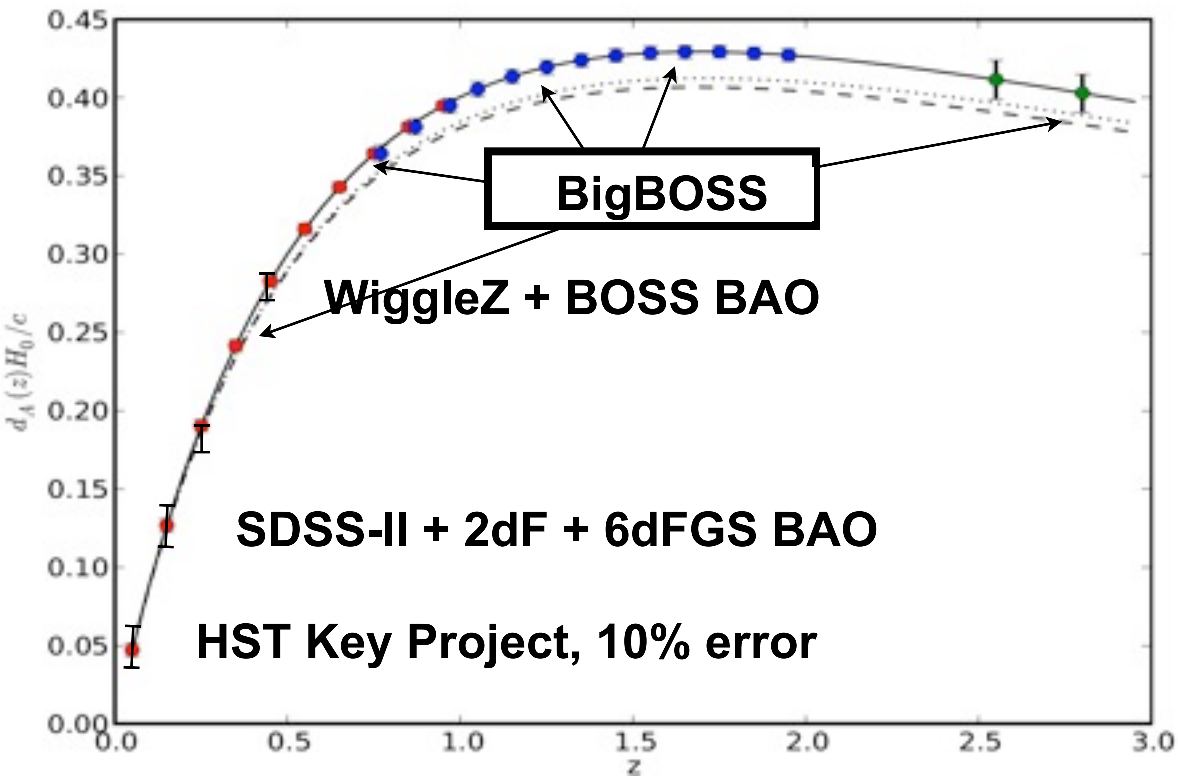


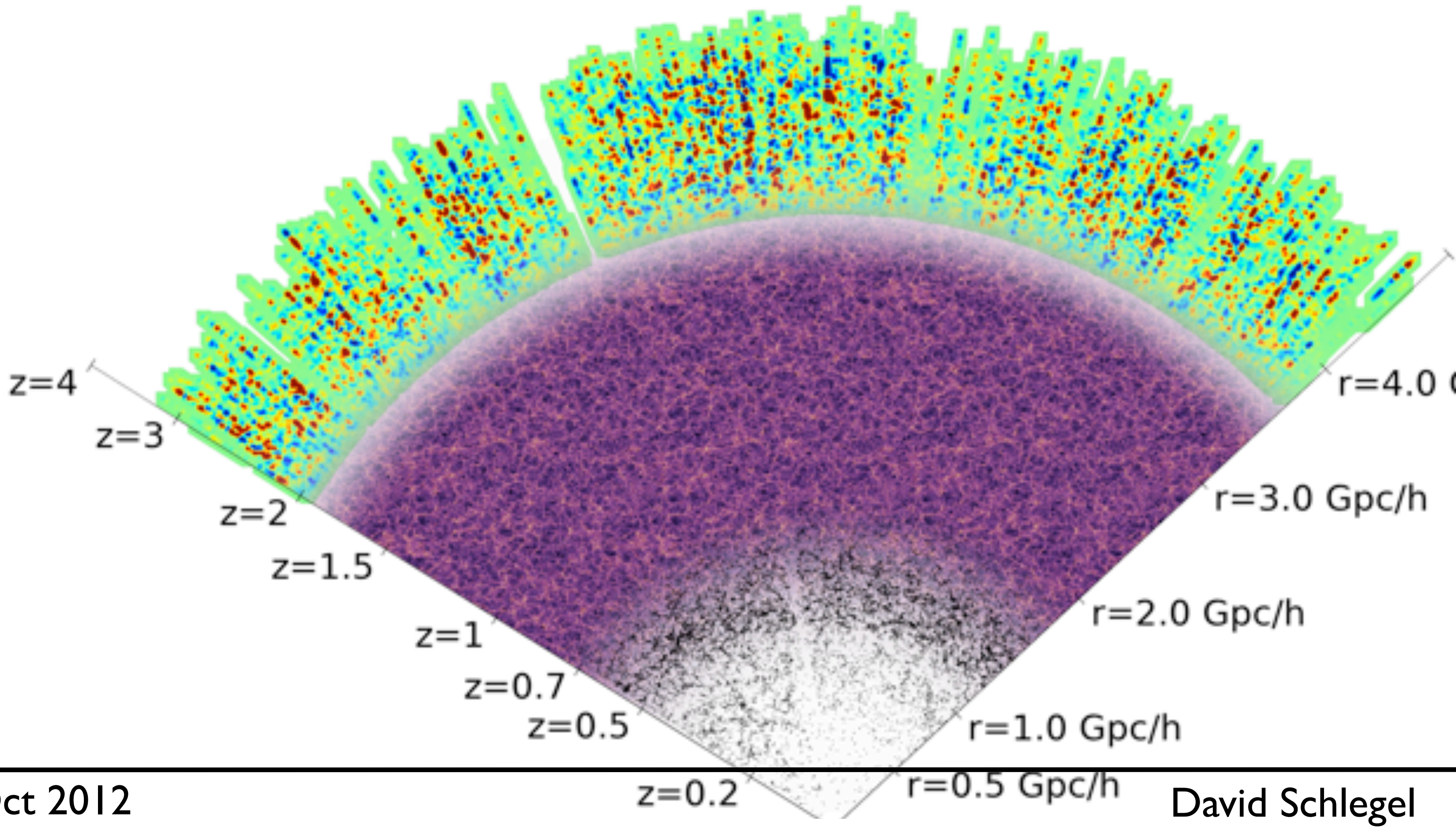
Warning #1: Analyzing future data sets

BOSS sampling luminous red galaxies

➔ ***Massive halos, easy to model***

BigBOSS + future surveys mapping lower-mass galaxies

➔ ***Requires much better N-body simulations!***



Warning #2: Analyzing future data sets

Systematics in target selection?
In BOSS: Largest systematics correlated with stellar densities

Work begun by Ashley Ross++
and Daniel Weisz, Shirley Ho++

Ameliorating Systematic Uncertainties in the Angular Clustering of Galaxies: A Study using SDSS-III

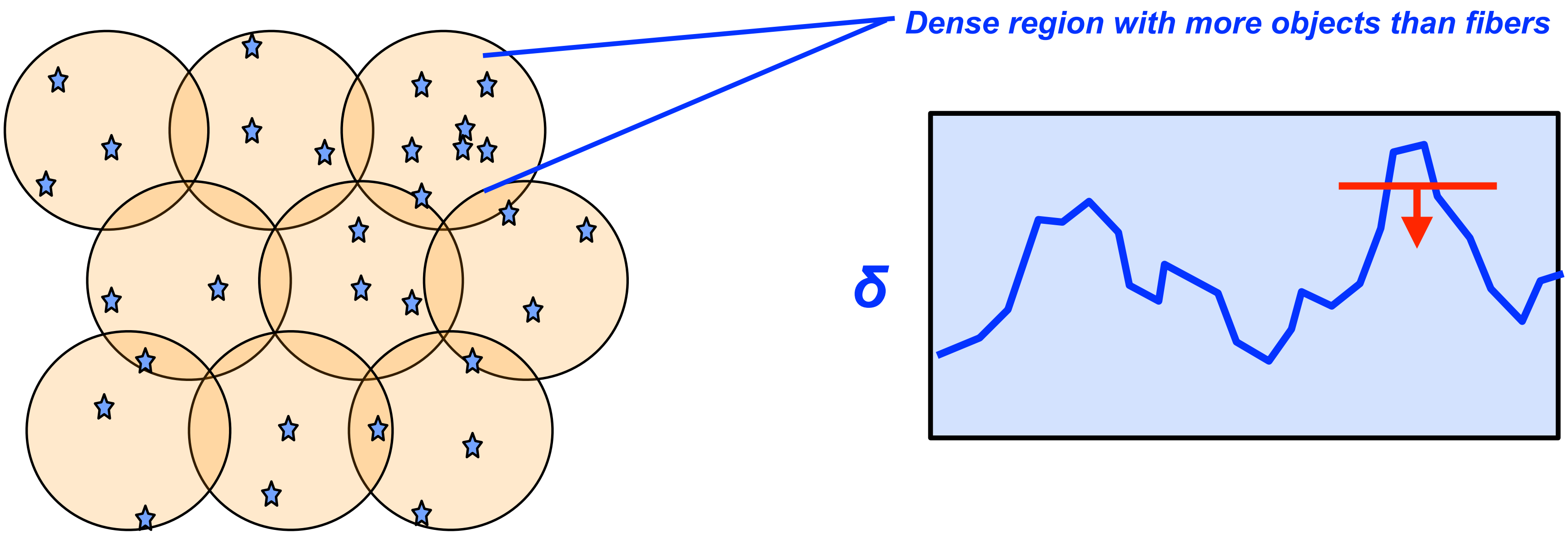
Ashley J Ross, Shirley Ho, Antonio J. Cuesta, Rita Tojeiro, Will J. Percival, David Wake, Karen L. Masters, Robert C. Nichol, Adam D. Myers, Fernando de Simoni, Hee Jong Seo, Carlos Hernandez-Monteagudo, Robert Crittenden, Michael Blanton, J. Brinkmann, Luiz A. N. da Costa, Hong Guo, Eyal Kazin, Marcio A. G. Maia, Claudia Maraston, Nikhil Padmanabhan, Francisco Prada, Beatriz Ramos, Ariel Sanchez, Edward F. Schlafly, David J. Schlegel, Donald P. Schneider, Ramin Skibba, Daniel Thomas, Benjamin A. Weaver, Martin White, Idit Zehavi

(Submitted on 11 May 2011 (v1), last revised 1 Jul 2011 (this version, v2))

We investigate the effects of potential sources of systematic error on the angular and photometric redshift, z_phot, distributions of a sample of redshift $0.4 < z < 0.7$ massive galaxies whose selection matches that of the Baryon Oscillation

Warning #3: Analyzing future data sets

All future redshift surveys will use robotic fibers
Cannot fully sample high-density regions



Positives: More objects, better statistical errors on P(k)

Negatives: P(k) depends on density field
Introduces 1-2 Mpc scale
Especially bad for >2-point statistics

Warnings: Analyzing future data sets

Problems common to any future, precision cosmology experiments
Many excellent papers awaiting to be written!

P(k) → BAO, RSD, neutrino masses, ...

$$\frac{\delta(\text{Cosmology})}{\delta(\text{Experiment})} \rightarrow 0$$

Experimental design:
Instrument, target selection, tiling, spectra →z's