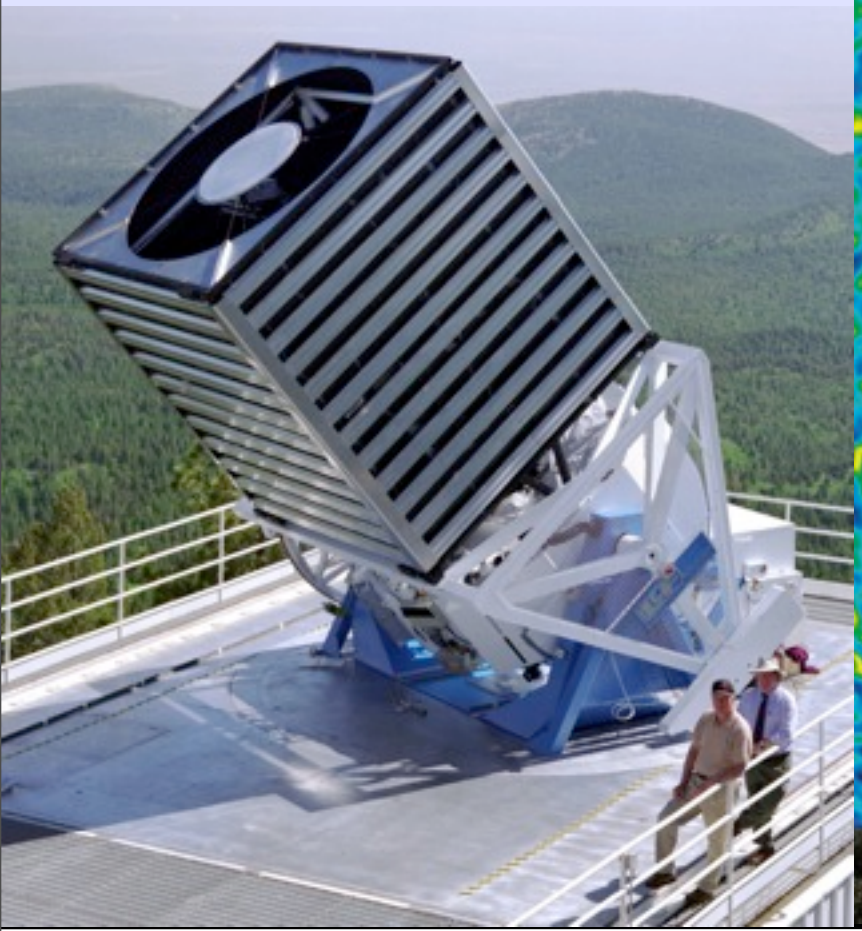
BOSS:
Ground-Based Stage III
BAO Experiment



BigBOSS:
Ground-Based Stage IV
BAO Experiment

Science Goals

Test the standard model

Quantum fluctuations -- early Universe permitted because $\Delta E \Delta t < \hbar$
Early Universe inflation by 10^{55}
Leads to scale-free fluctuations
Gravitation growth of structure
(Einstein gravity)

N-body simulation credit: C4 collaboration, Thaker & Couchman

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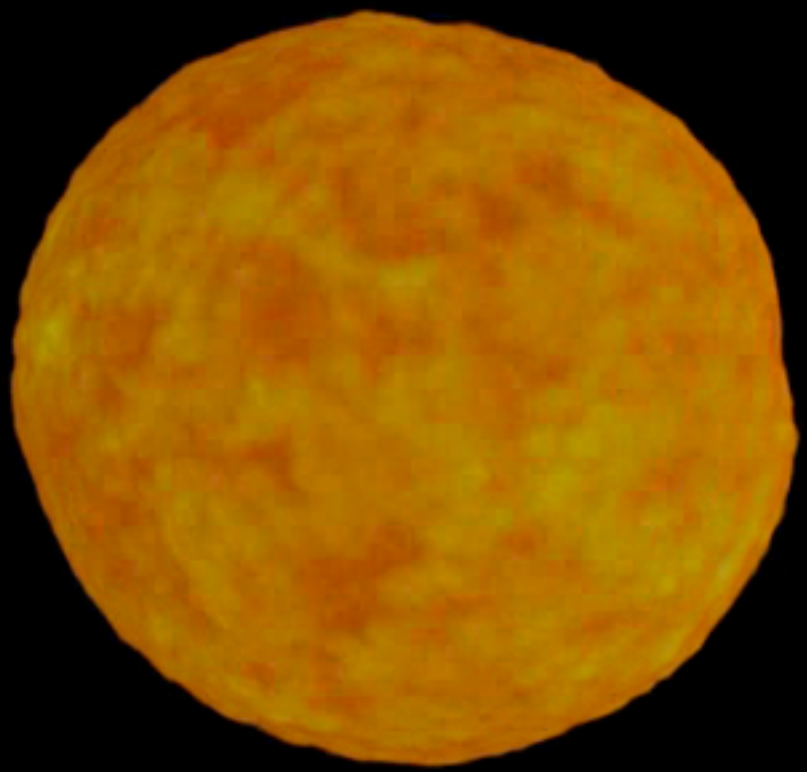
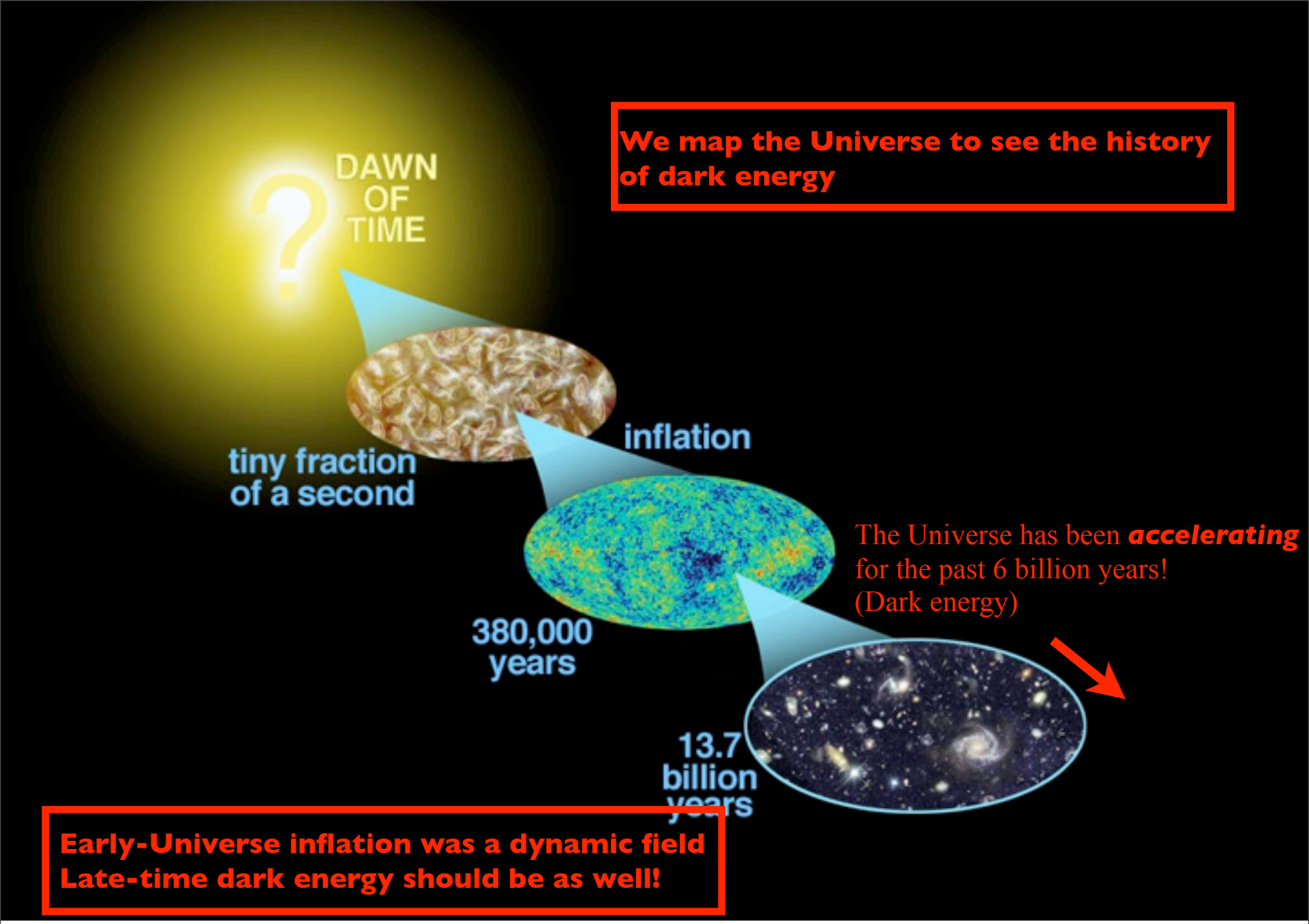


N-body simulation credit: C4 collaboration, Thaker & Couchman

We map the Universe to see the history of dark energy



Early-Universe inflation was a dynamic field
Late-time dark energy should be as well!

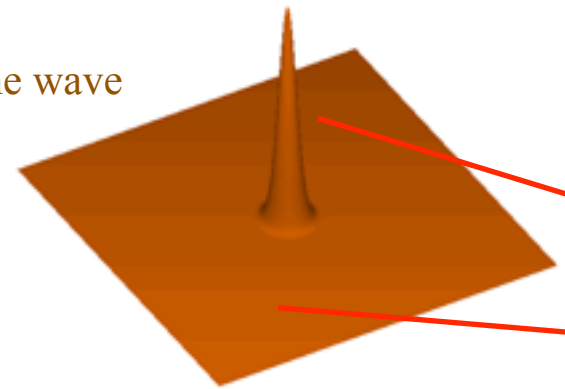
Why map the sky?

Baryon Acoustic Oscillations (BAO)

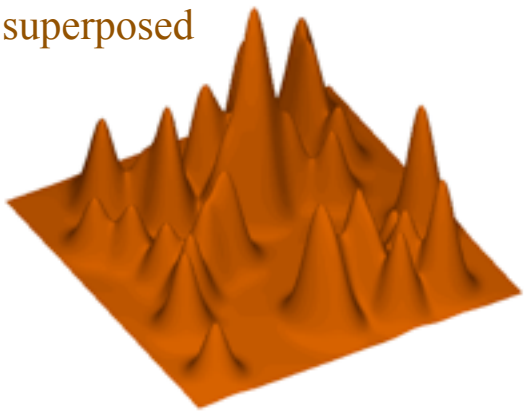
Sound waves traveled 500 million light years in the plasma of the early Universe, then abruptly stopped.

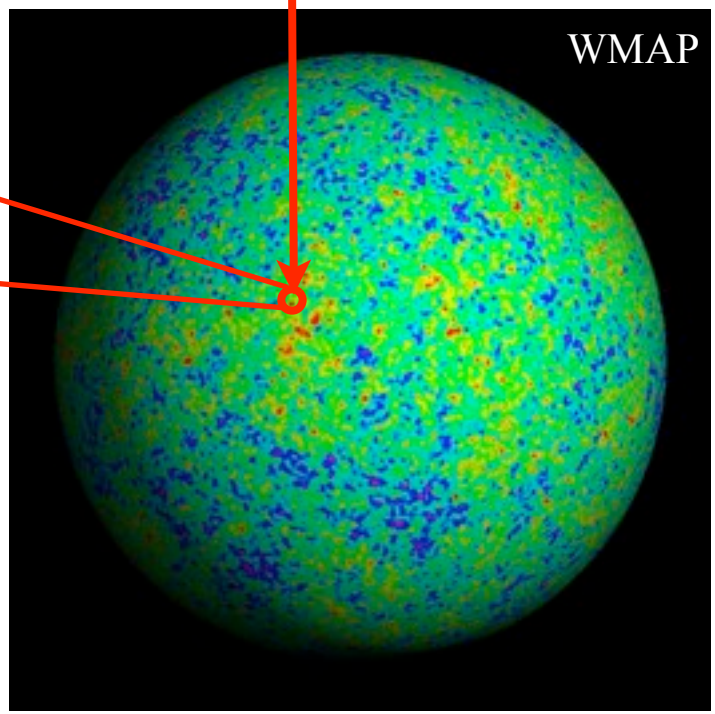
We can use this as a "***standard ruler***"

One wave



Many superposed waves





Map of Universe at 400,000 years (CMB)

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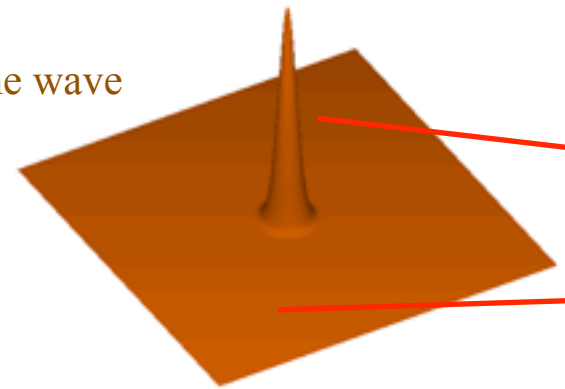
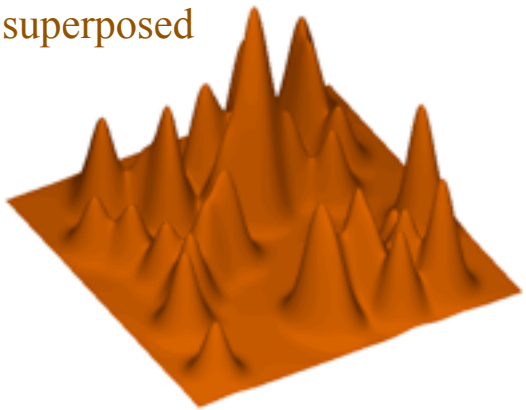
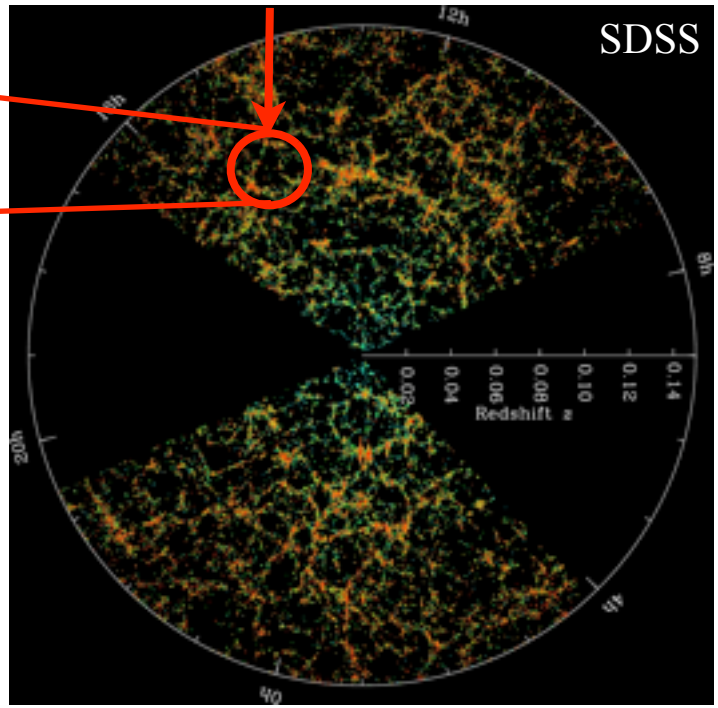


Many superposed waves



We can use this as a "***standard ruler***" (if a little inconveniently long!)



Map of galaxies today

Why map the sky?

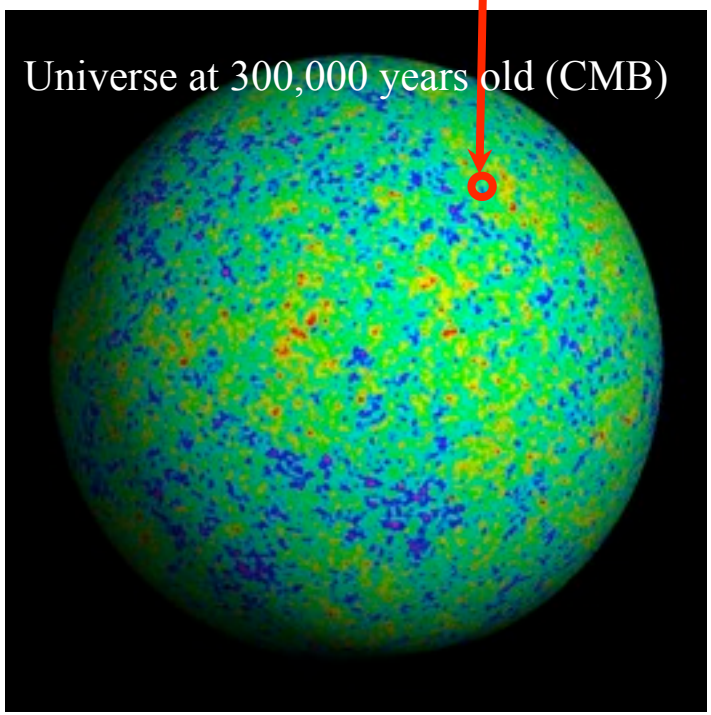
Baryon Acoustic Oscillations (BAO)

Precision dark energy probe from BAO scale

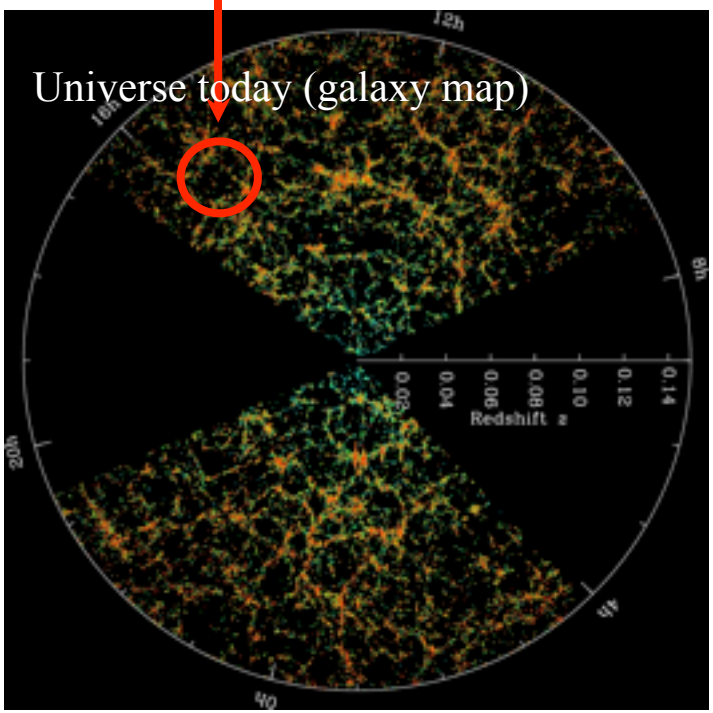
Inflation probe from non-gaussian fluctuations

- Better than Planck or JDEM

These fluctuations of 1 part in 10^5 gravitationally grow into...



...these ~unity fluctuations today



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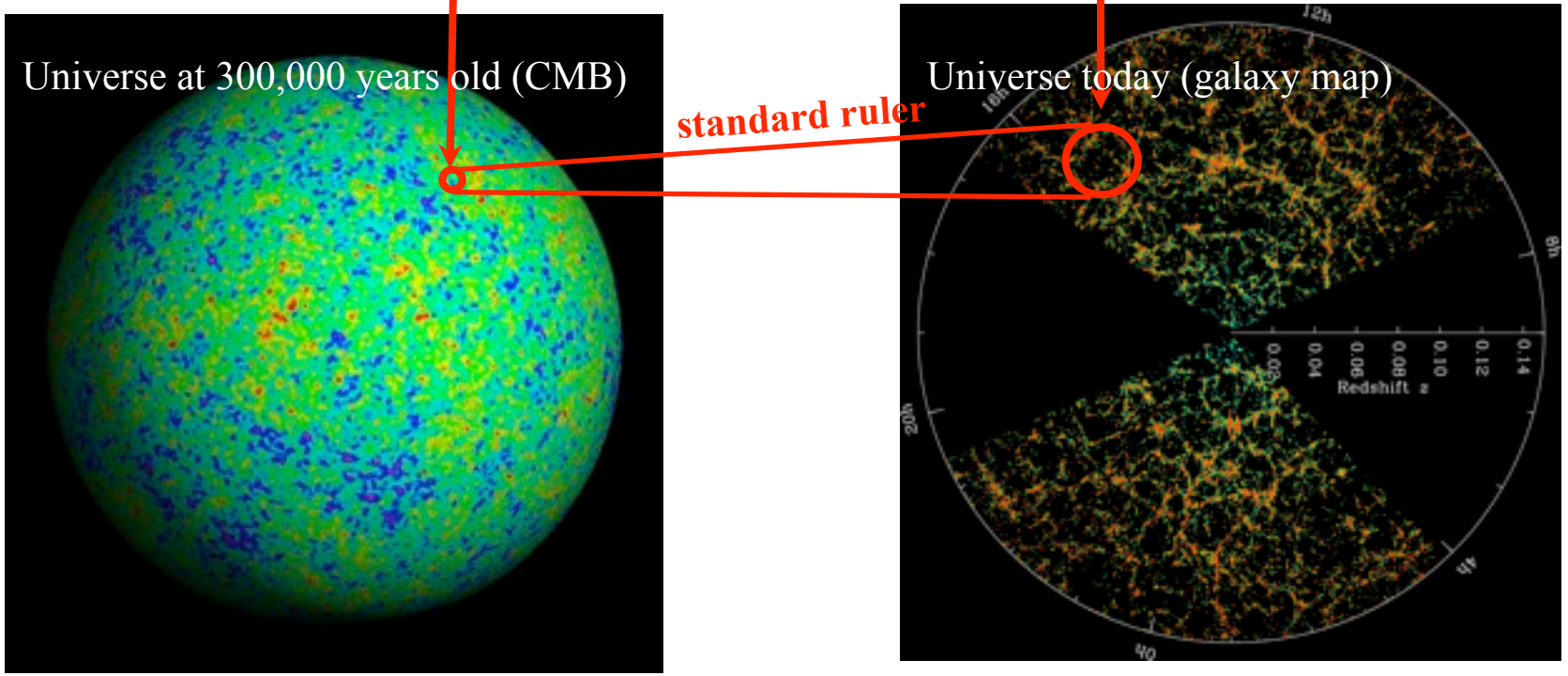
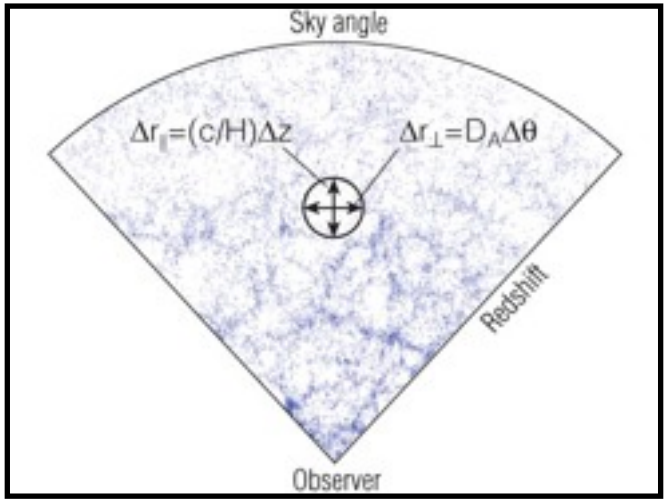


BAO and dark energy

What we like...

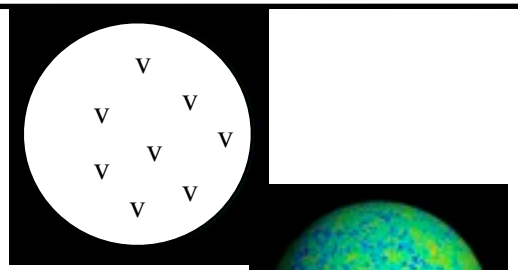
- Like supernovae, a geometrical probe of the expansion rate (and dark energy)
- The acoustic oscillation scale depends on the sound speed and the propagation time
- Anchored at recombination (z=1088) by the CMB
- Orientation of ruler provides two different probes
  - Transverse rulers probes $D_A(z)$
  - Line of sight rulers probe $H(z)$
- These depend on the matter-to-radiation ratio ($\Omega_m h^2$) and the baryon-to-photon ratio ($\Omega_b h^2$)
- Only need to make 3D maps (angles + redshifts)

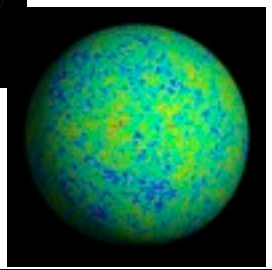


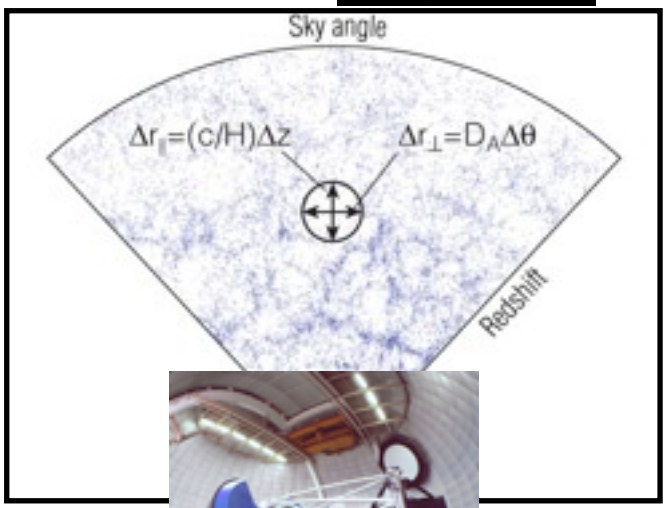
What we don't like...

- Ruler is inconveniently long → 150 Mpc = 450 million light years
- Statistical measure of a small signal → Requires mapping millions of objects
- There is a cosmic variance limit... once we reach that, we're done!

BAO and dark energy







BAO: What tracer objects to use?

$z=10^{11}$ Neutrino background
(not for BAO ruler, but horizon at ν decoupling)

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

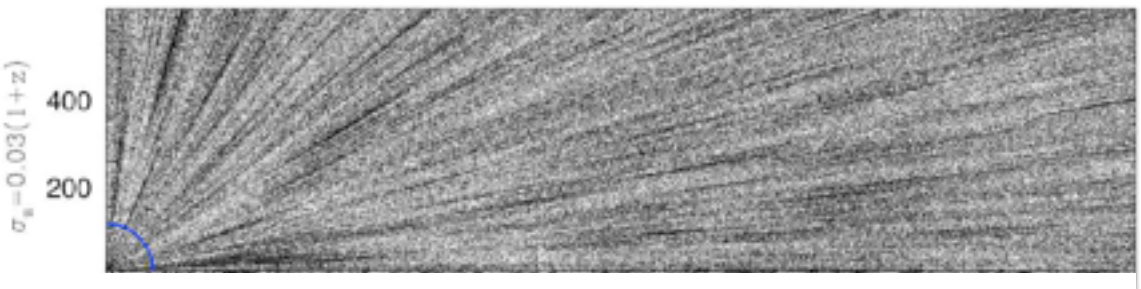
z=0

All existing BAO measurements

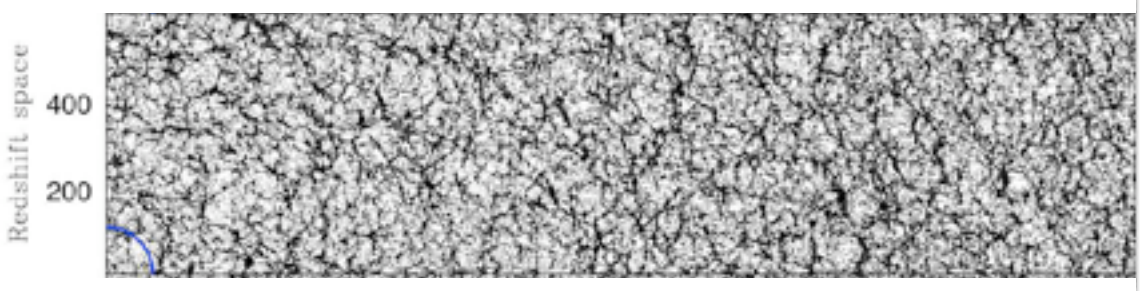
Definitely the hard way,
but it's been suggested!
(Angulo et al 2006)
(Zhan et al 2008)

BAO and dark energy

Spectroscopic surveys, not photometric!
BAO from imaging-only surveys smears signal
DETF figure-of-merit reduced by 5X



imaging only (photo-z map)

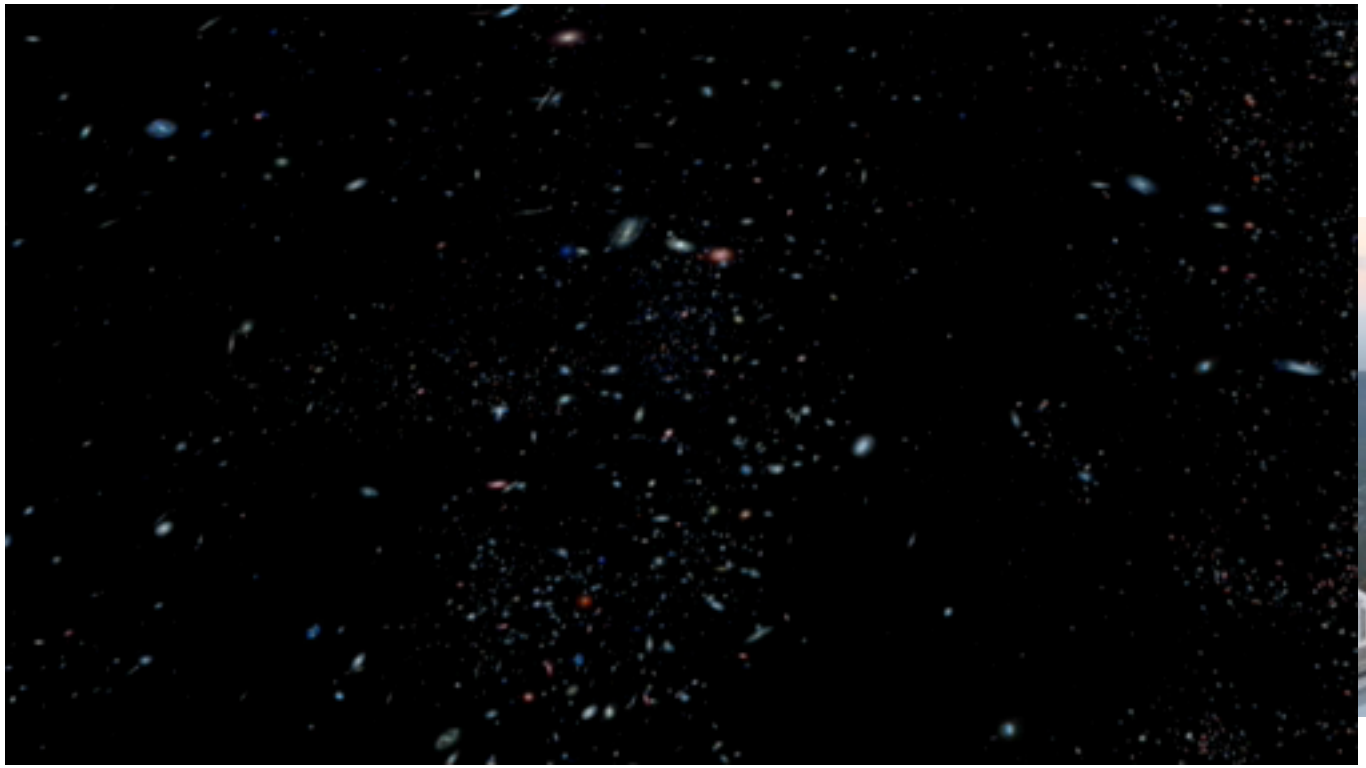


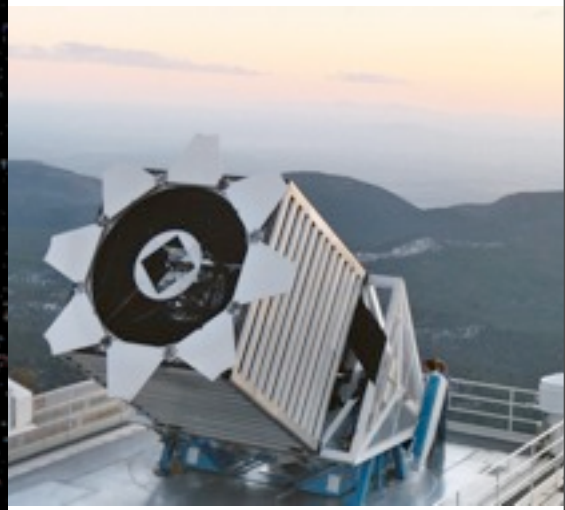
spectroscopic-redshift map

BAO from 3-D maps: SDSS

Finally technologically possible

Sloan Digital Sky Survey (SDSS) telescope
⇒ **Optical design** for large focal plane: 7 deg^2
⇒ **Fiber-fed** spectrographs: 640 redshifts simultaneously





SDSS telescope,
Apache Point, New Mexico

Next-Generation BAO Experiment: BOSS == Baryon Oscillation Spectroscopic Survey

A variety of facilities considered for next-gen BAO experiment:
Lick 3-m, Keck 10-m, MMT 6.5-m, ...

SDSS telescope secured for next-gen BAO experiment:
July 2006: Competitive proposal to use (upgraded) SDSS telescope for next-gen BAO
Nov 2006: BOSS proposal selected for all dark+grey time for 2009-2014
Feb 2007: DOE R&D proposal for upgrading SDSS spectroscopic system
Sep 2007: Commitment from Alfred P. Sloan Foundation
June 2008: Commitment from NSF
Jan 2009: Commitment from DOE

Partners:

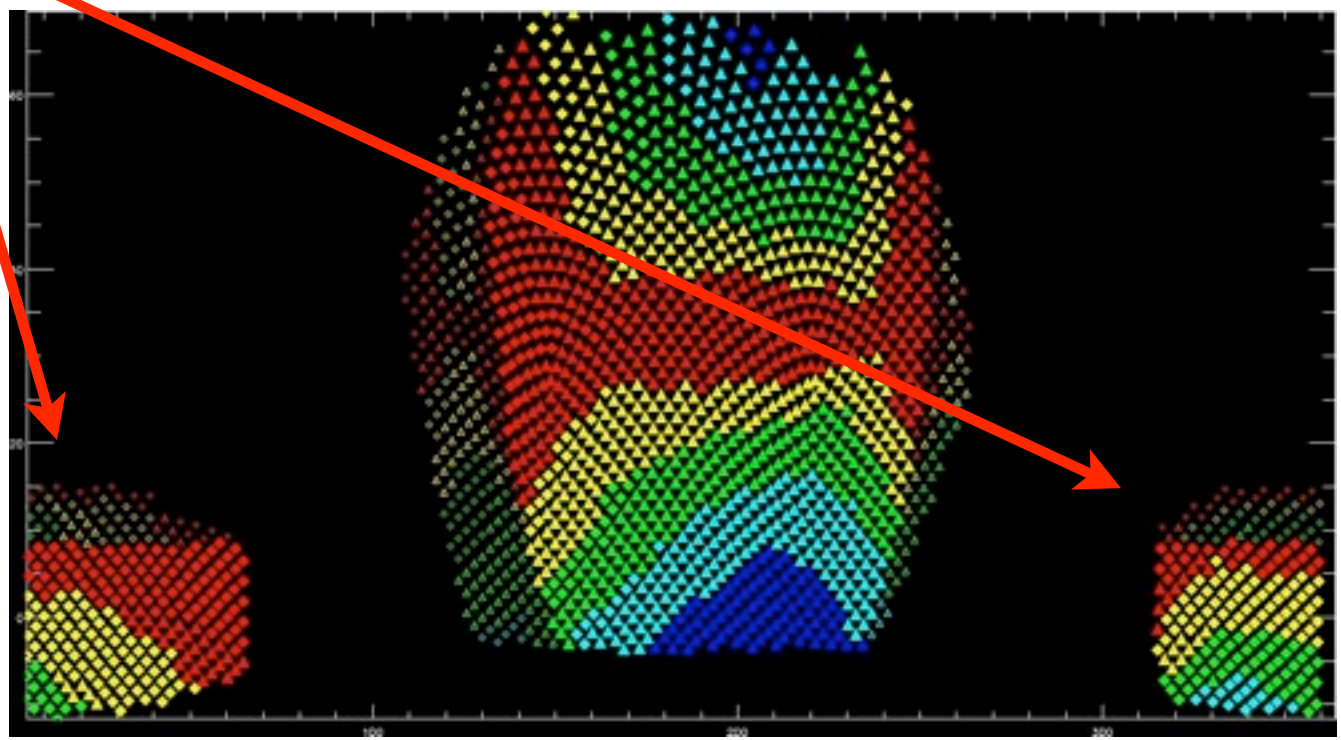
- Univ. of Arizona
- Brazilian Participation Group
- Cambridge Univ.
- Case Western Univ.
- Univ. of Florida
- French Participation Group
- Univ. of Heidelberg
- Johns Hopkins Univ.
- IMPU Institute (Japan)
- Korean Institute for Advanced Study
- Lawrence Berkeley Lab
- Los Alamos National Lab
- MPA Garching
- Michigan State Univ/JINA
- New Mexico State Univ.
- New York Univ.
- Ohio State Univ.
- Penn State Univ.
- Univ. of Pittsburgh
- Univ. of Portsmouth
- Astronomical Institute Potsdam
- Princeton Univ.
- UC Santa Cruz
- Univ. of Utah
- Univ. of Virginia
- Univ. of Washington

BOSS == Baryon Oscillation Spectroscopic Survey at SDSS telescope

All targets selected from SDSS
Requires 10,000 deg^2 footprint
→ SDSS imaging of additional 2000 deg^2 in Fall 2008

BOSS footprint
Additional 2000 deg^2

SDSS & SDSS-II
footprint
8000 deg^2

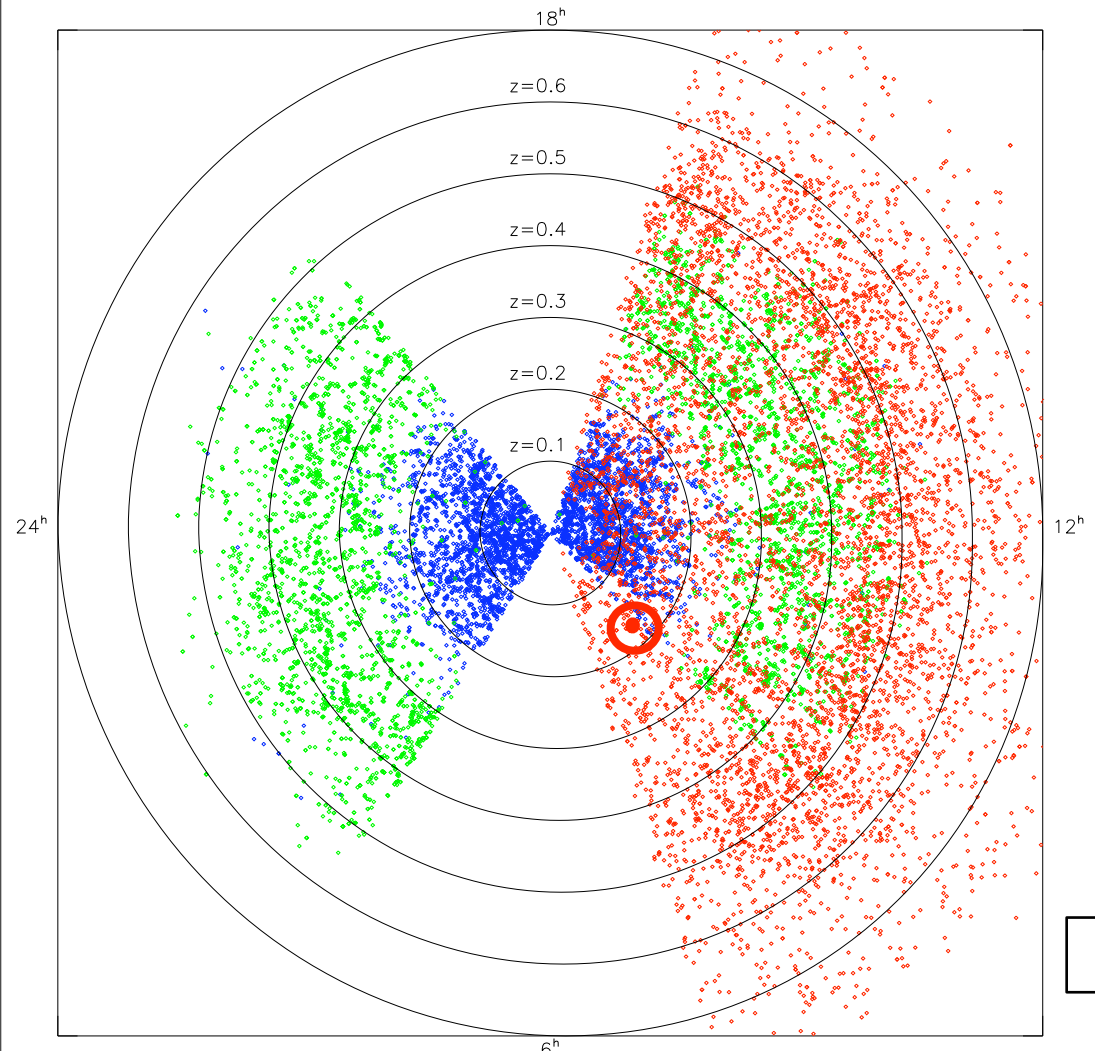


BOSS == Baryon Oscillation Spectroscopic Survey at SDSS telescope

Two simultaneous spectroscopic surveys from 2009-2014

➙ **BAO from 1.3 million galaxies at z=0.3, 0.6**

➙ BAO from 160,000 QSOs at 2.2<z<3



SDSS main galaxy survey
~1 million galaxies
Too little volume for BAO

SDSS luminous red galaxies (LRGs)
Sparse sampled at 10^{-4} galaxies/Mpc^3
47,000 galaxies by 2004
80,000 galaxies by 2008
8000 deg^2 (finish in 2008)

BOSS red galaxies
10,000 deg^2
5x sample density (shot noise)
2x volume

Turn this photo-z sample ➙ spectro-z

BOSS == Baryon Oscillation Spectroscopic Survey at SDSS telescope

Two simultaneous spectroscopic surveys from 2009-2014
- ~~BAO from 1.3 million galaxies at z=0.3, 0.6~~
- **BAO from 160,000 QSOs at 2.2<z<3**

$$P_{\rm raw}(\mathbf{k}) = \left[P_F(\mathbf{k}) + n^{-1} P_F^{\rm 1D}(k_\parallel)\right] W^2\left(k_\parallel R\right) + P_N^{\rm eff}$$

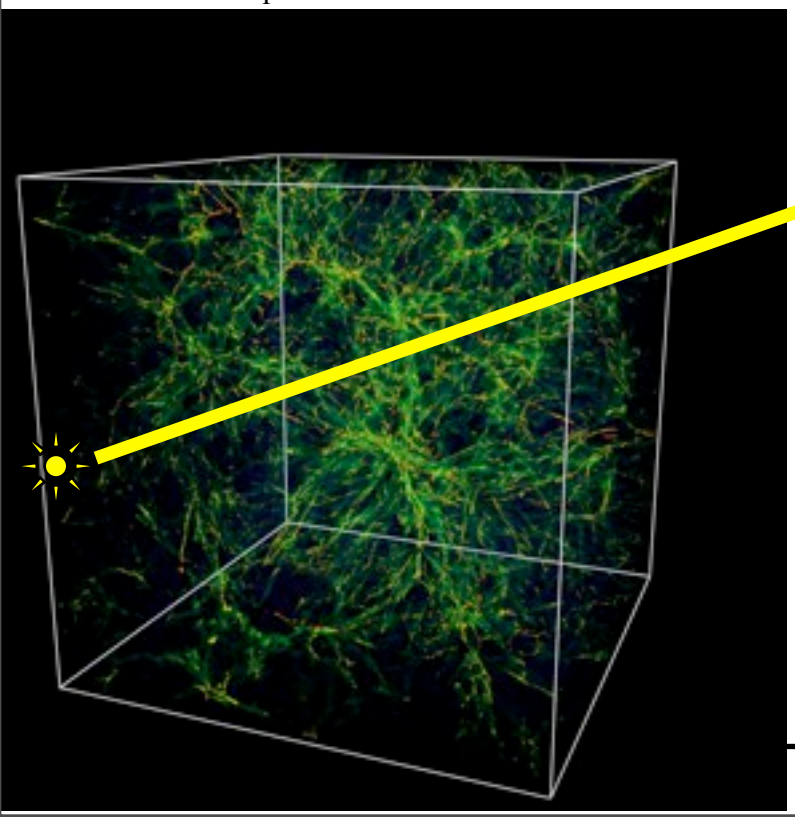
Ideal 3D power (perfectly sampled)

Sampling noise
n=surface density of lines of sight
(analogous to galaxy shot noise)

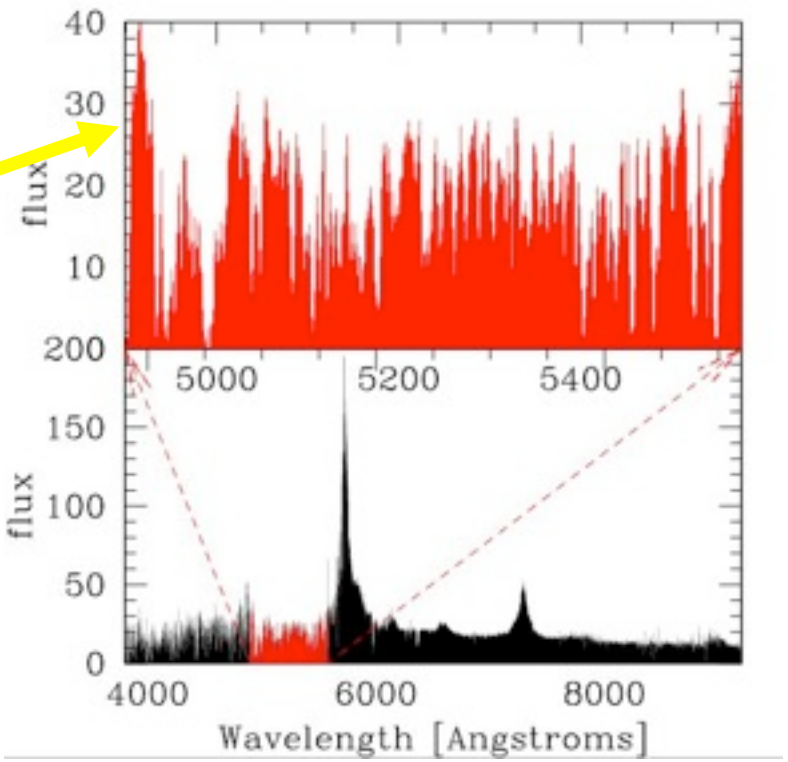
Resolution

Detector noise

Simulation of the IGM (R. Cen)
Neutral H in 25 h^{-1}Mpc box



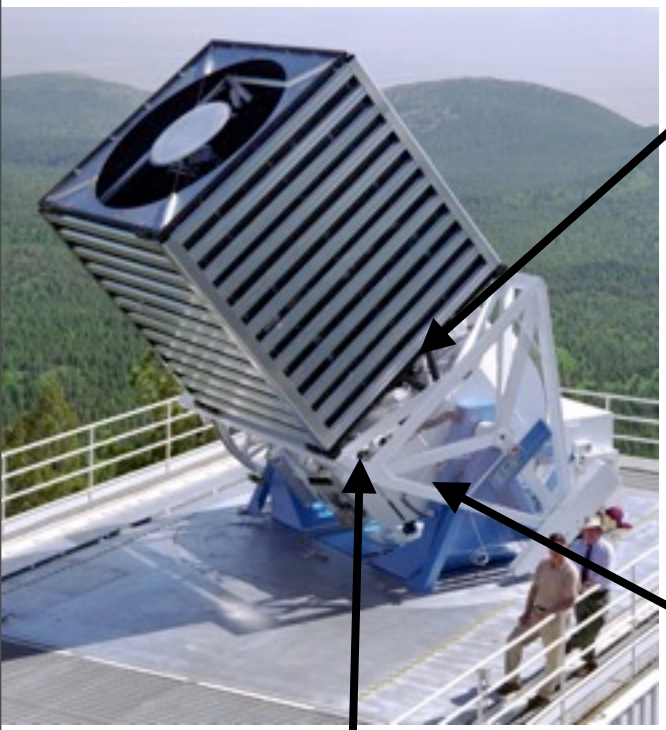
Ly forest in SDSS QSO spectrum at z=3.7



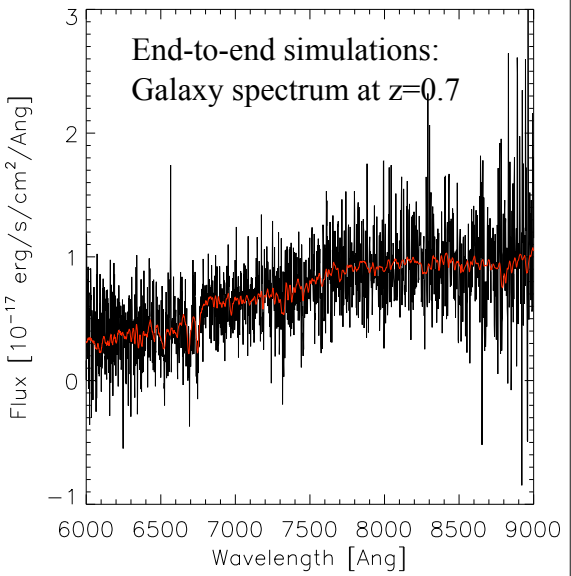
David Schlegel, Dome A, 21 Jul2009

BOSS status

Largest field-of-view of
any large telescope -- DONE!

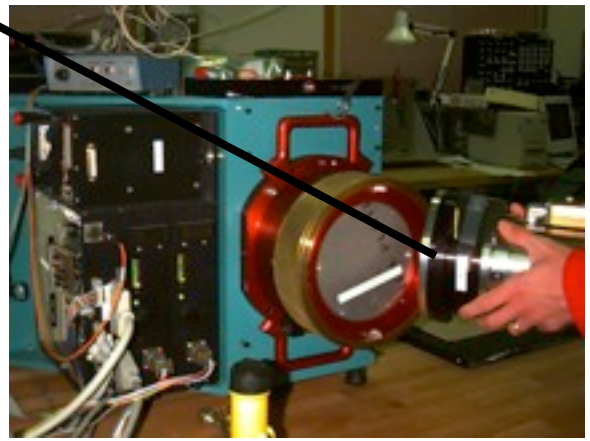


1000 small-core fibers to replace existing
(more objects, less sky contamination)



Software development underway

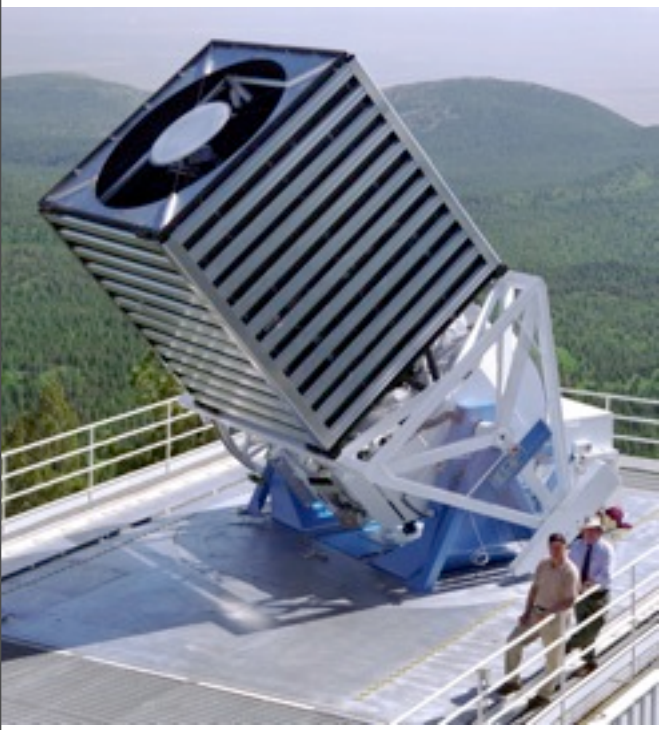
Swap gratings for VPH



Replace red CCDs w/red-sensitive **LBL/SNAP CCDs**, making it possible to go to higher-z

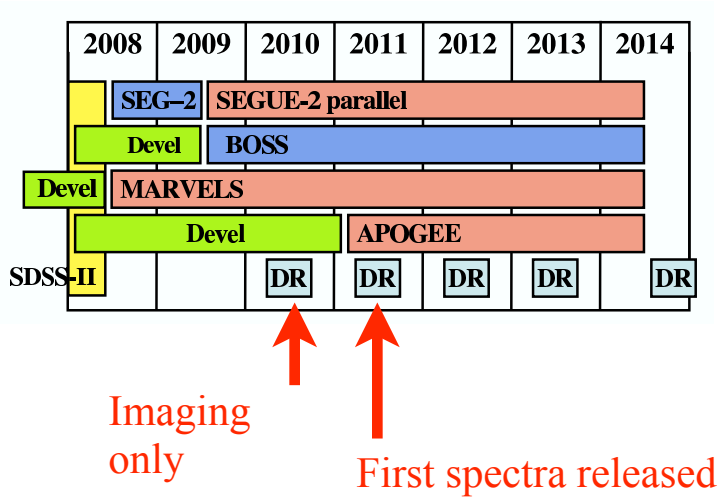
Replace blue CCDs w/UV-sensitive e2v CCDs, making it possible for Ly at z=2.3→3

BOSS status



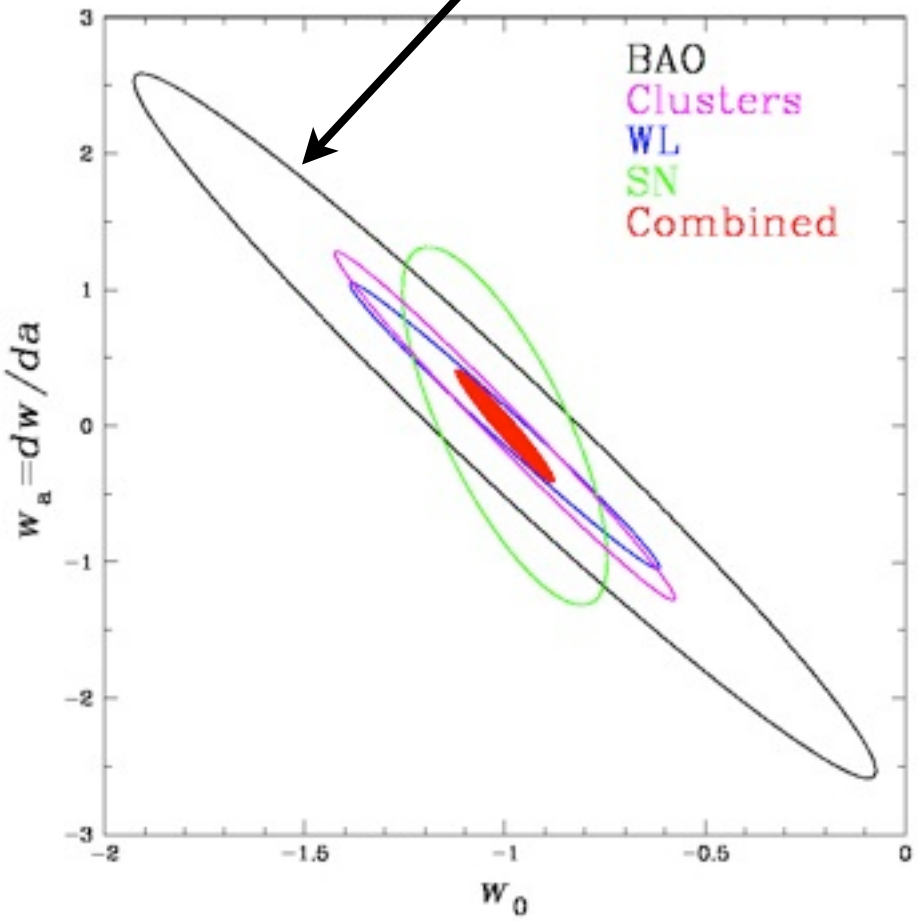
Observing Plan:

Fall 2008 + Fall 2009: Complete imaging survey
Summer 2009: Commissioning
Sep 2009: Begin survey
July 2014: End survey

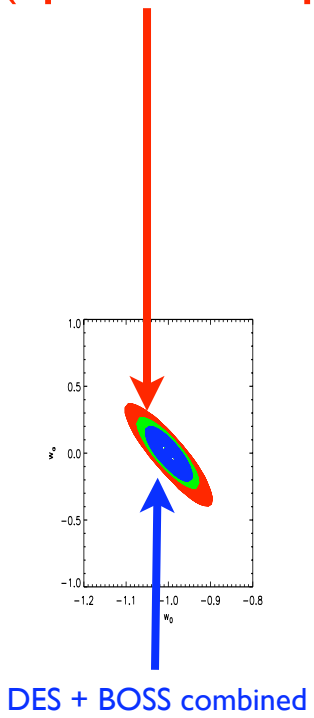


BOSS: Baryon Oscillation Spectroscopic Survey Complements Imaging-Only Surveys

BAO from Dark Energy Survey (imaging only)



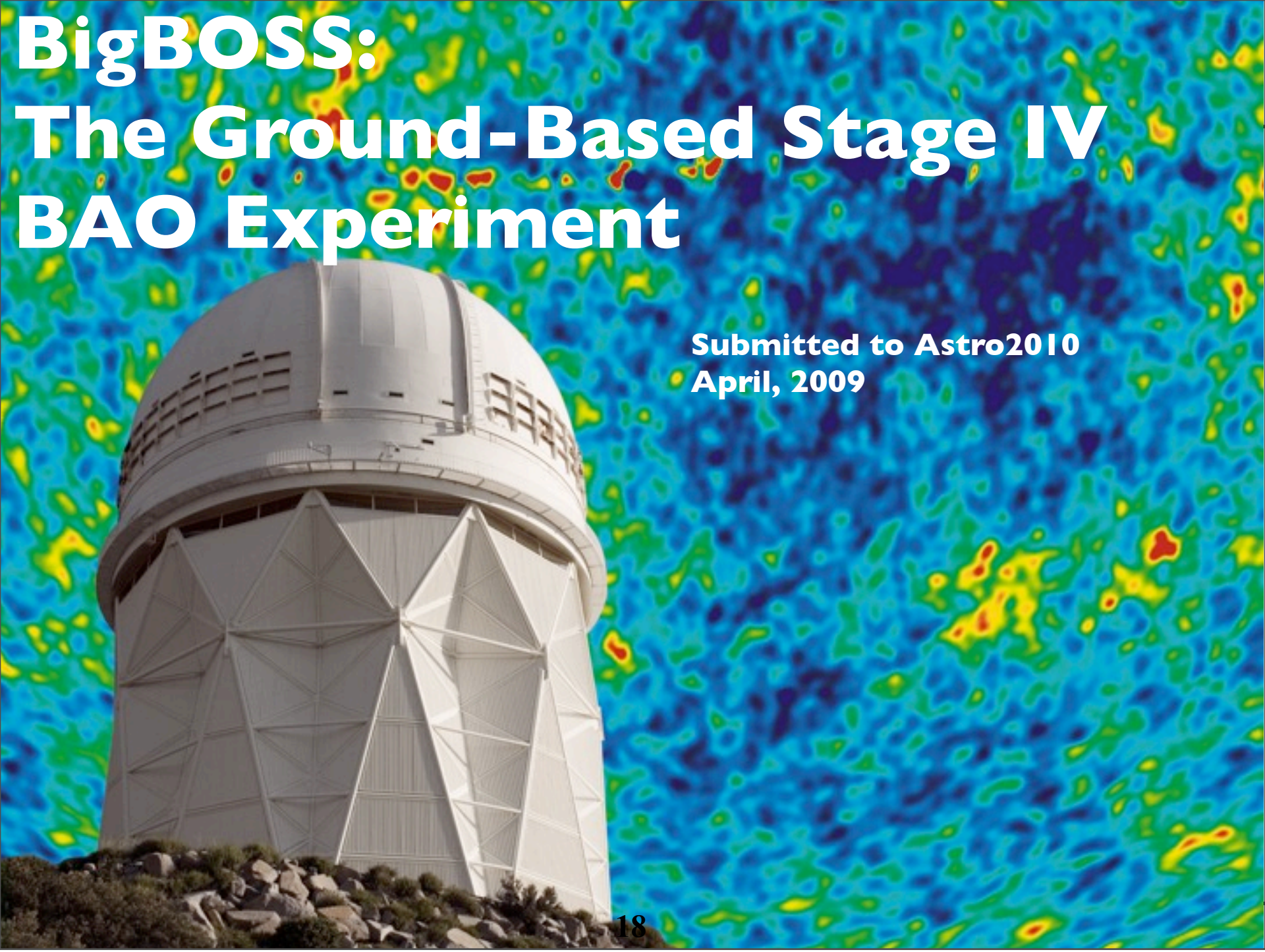
BAO from BOSS (spectroscopic)



DETF figure of merit = inverse area of ellipse

$$w(z) = w_0 + w_a(1-a)$$

BigBOSS: The Ground-Based Stage IV BAO Experiment



Submitted to Astro2010
April, 2009

The Ground-Based Stage IV BAO Experiment

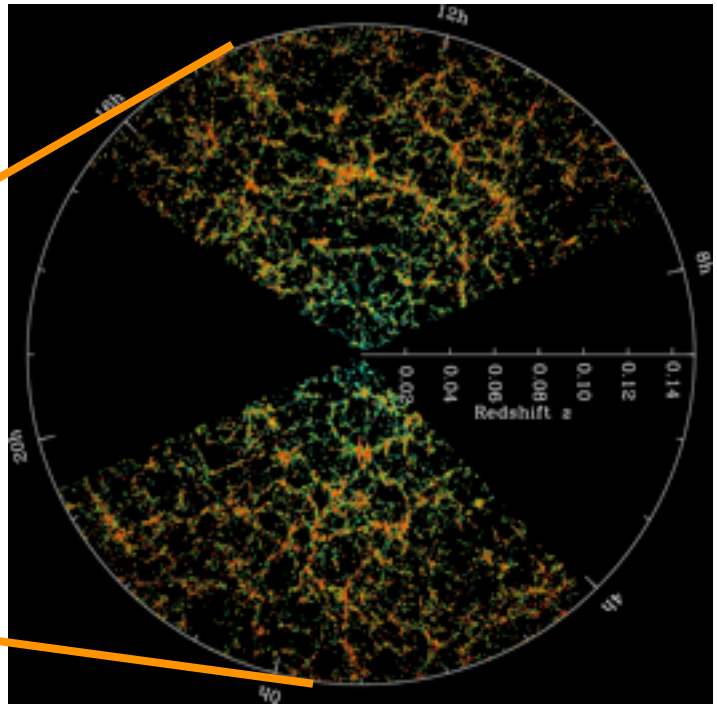
BigBOSS

Science Goals: 50 million redshifts

Sensitivity to new physics scales as volume surveys -- # of modes

Our observable Universe

Volume mapped by SDSS + SDSS-II



Volume to be mapped by SDSS-III/BOSS (ca. 2015)

Surface of last scattering

BigBOSS @NOAO

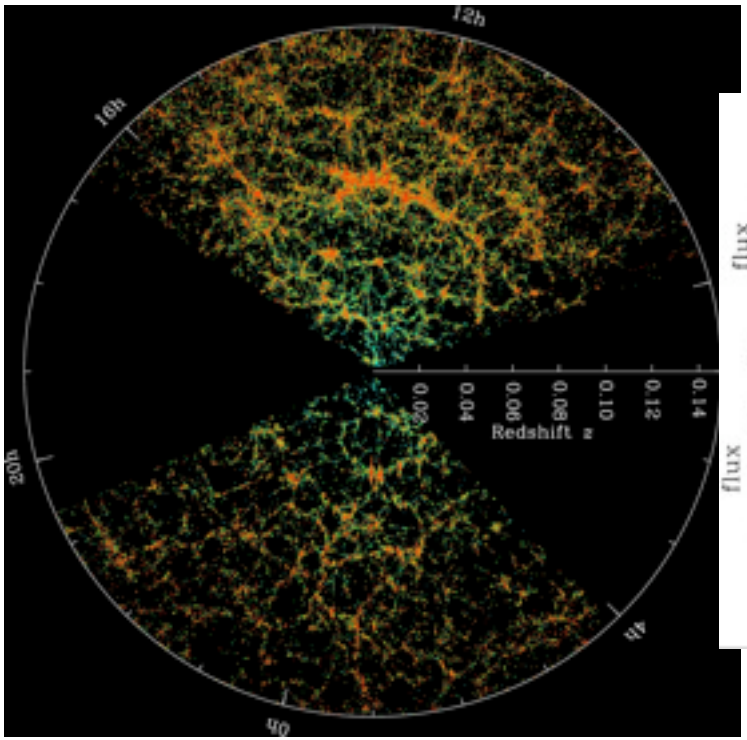
The Ground-Based Stage IV BAO Experiment

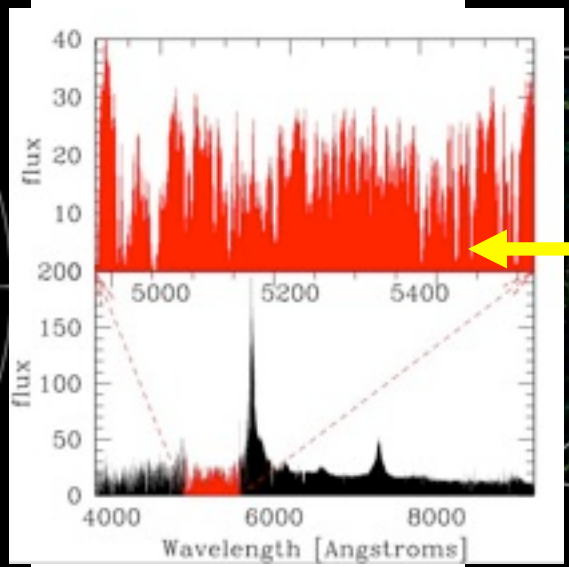
BigBOSS

Science Goals: 50 million redshifts

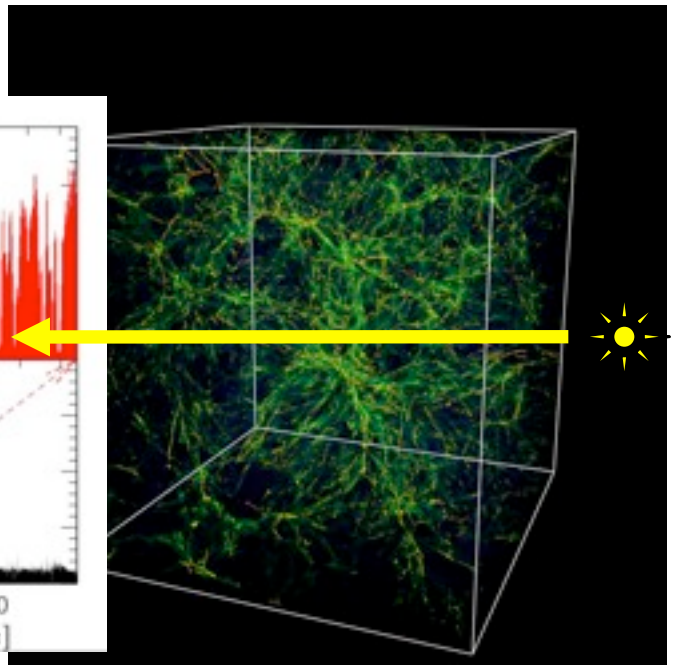
Simultaneous spectroscopic surveys from 2015-2025
- → BAO from 50 million galaxies at $0.2 < z < 2.0$
- → BAO from 1 million QSOs at $1.8<z<3$

Galaxy map





QSOs as back-light to hydrogen gas

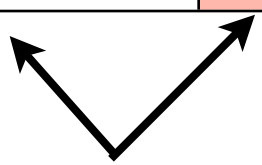


The Ground-Based Stage IV BAO Experiment

BigBOSS

Science Goals: BAO and dark energy

	BOSS (Stage III)	BigBOSS-North (Stage IV)	JDEM (Stage IV)	BigBOSS-N+S (Stage IV)
Redshift range	**0<z<0.7**	**0<z<3.5**	**0.7<z<2.0**	**0<z<3.5**
Sky Coverage	10000 deg^2	14000 deg^2	20000 deg^2	24000 deg^2
Wavelength Range	360-1000 nm	340-1130 nm	1100–2000 nm	340nm–1130 nm
Spectral Resolution	1600-2600	2300-6100	200	2300-6100
DETF FoM	57	175	250	286
DETF FoM w/Stage III	**107**	**240**	**313**	**338**



BigBOSS has same science reach as $1.7B JDEM satellite

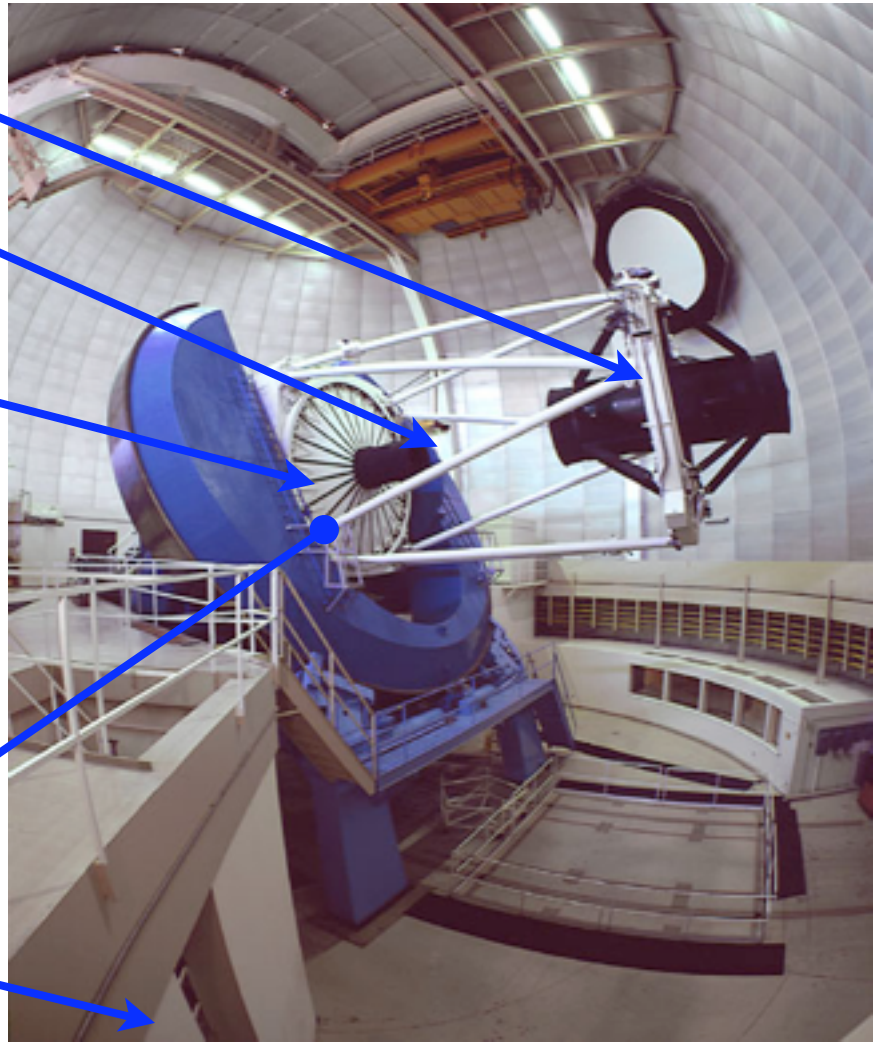
BigBOSS could field on KPNO 4m + CTIO 4m

Science Goals: Summary

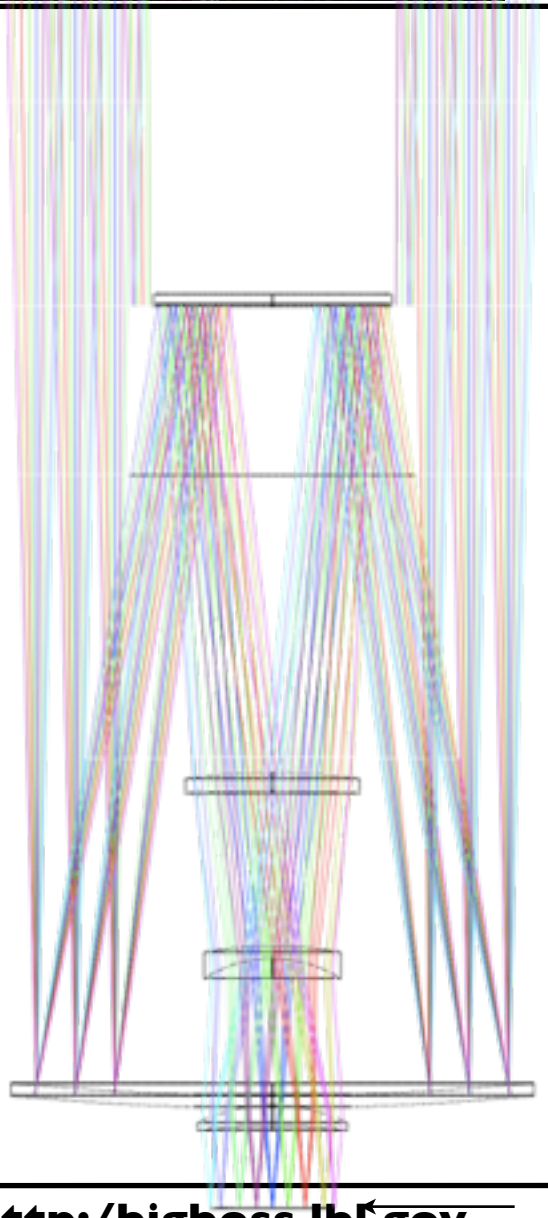
- **"Stage-IV" dark energy experiment from the ground**
  - Higher performance than JDEM-BAO satellite
  - Lower risk + greater flexibility
- **Physics beyond the standard model**
  - More linear modes than CMB == higher sensitivity to non-gaussianity from inflation
- **Enhances future imaging surveys (DES, LSST)**
  - Adds spectroscopic capability, eg. for SNe follow-up
  - Calibrates LSST photo-z's for WL
- **Requires only 4-m telescope time**
  - North: Kitt Peak (4m)
  - South: CTIO (4m)

Instrument: Telescope

Kitt Peak 4-m (Mayall) at Kitt Peak, Arizona

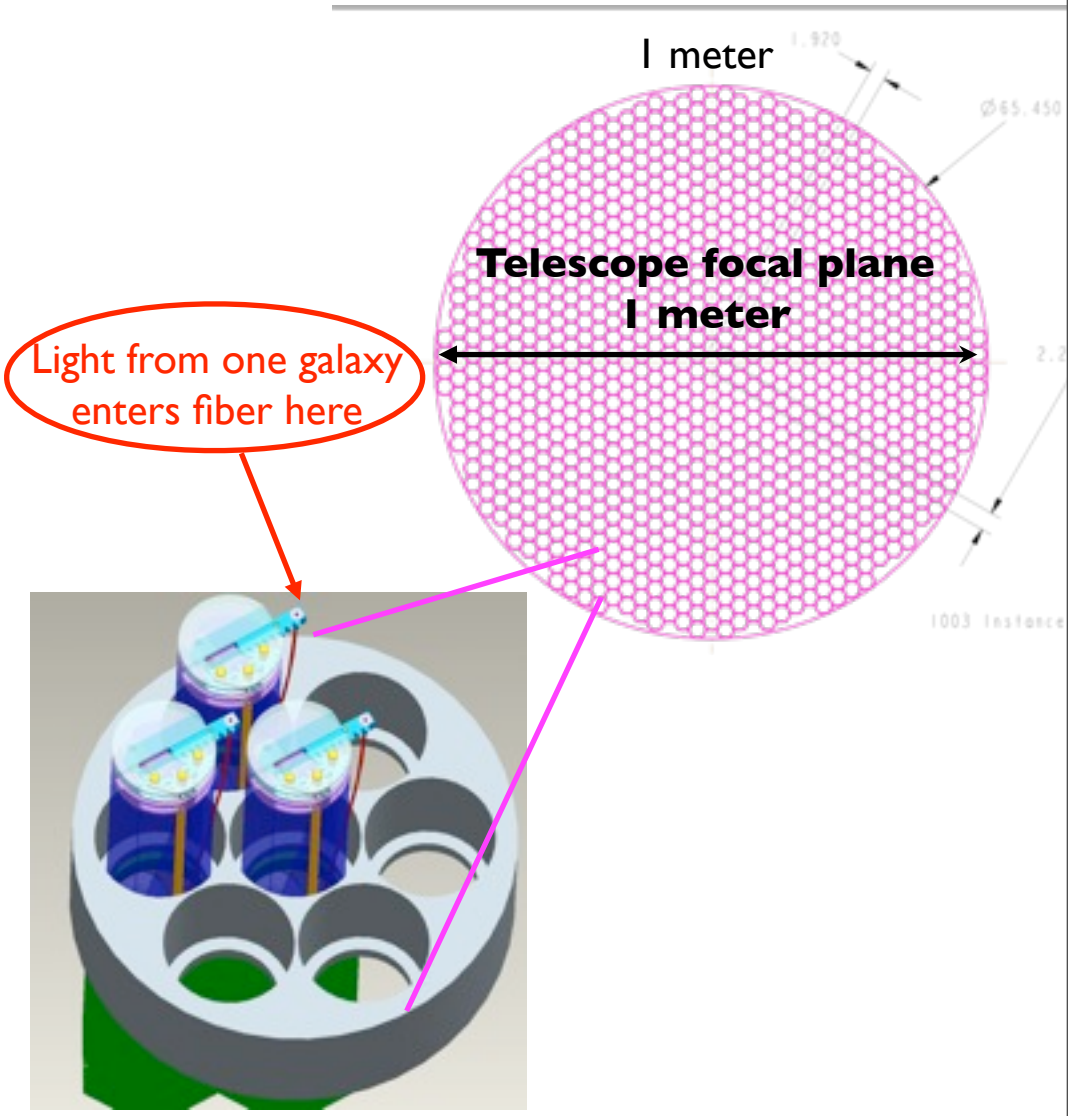


Instrument: Telescope optics



- Mayall is slow RC, making correction to **3º field** possible
- All magnification is in secondary
- Corrector lenses add no power
  - *Simple fused silica*
  - *No CaF*
- Manufacturing feasibility verified by the University of Arizona College of Optical Sciences
  - *Less challenging than previous optics, using profilometry + interferometry*
- Identical optics work at KPNO 4m + CTIO 4m

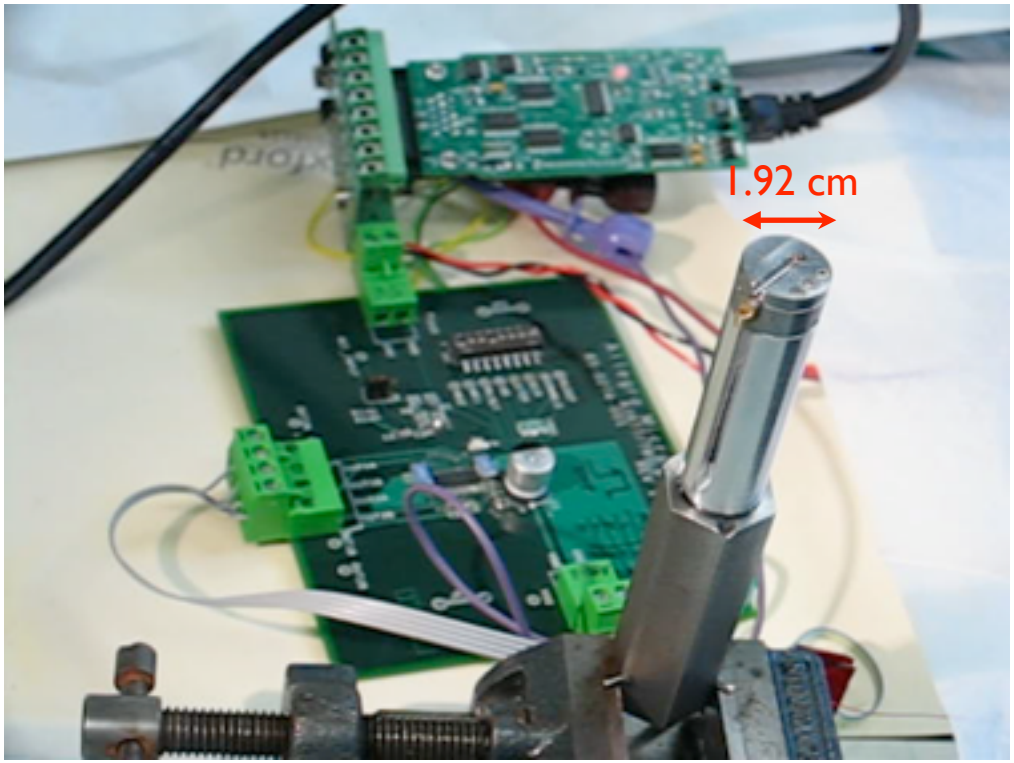
Instrument: Fiber positioners x 5000



Instrument: Fiber positioners x 5000

LBNL prototype

Scale is 1.92 cm center-to-center on this prototype
New design 1.10 cm

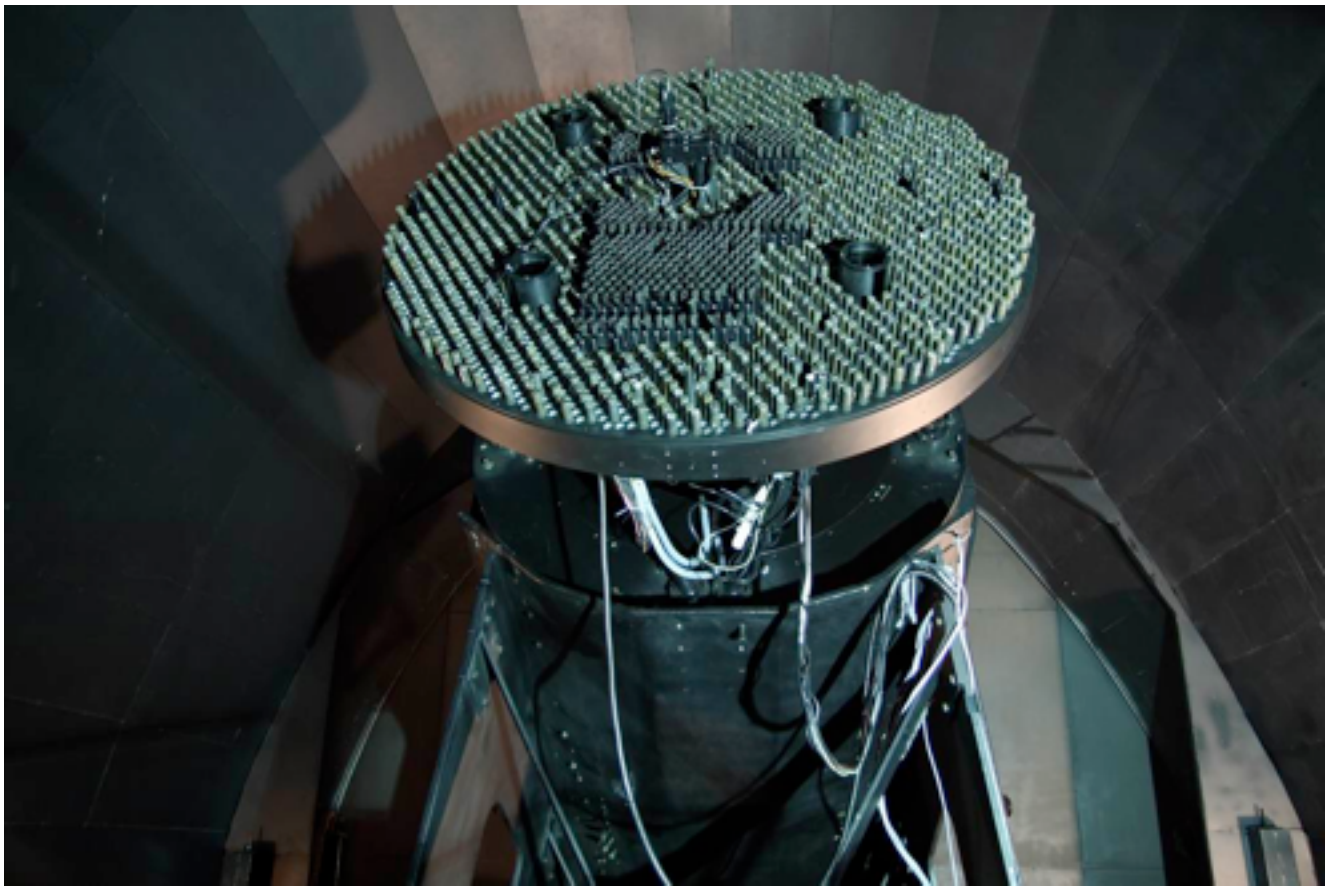


Divide into 5000 hex cells on 83 cm diameter focal plane
Each fiber is ***individually actuated*** with 2 Swiss motors
Local accuracy is only 1 part in 700 for 15 micron precision
Fiber reach extends slightly to adjacent cells - No dead space
Reconfiguration time < 1 min

Instrument: Fiber positioners x 5000

Collaboration with USTC in Hefei, China

Experience building LAMOST fiber positioners
Similar design (2 rotation axes with Micromo motors) at 2.54 cm center-to-center spacing

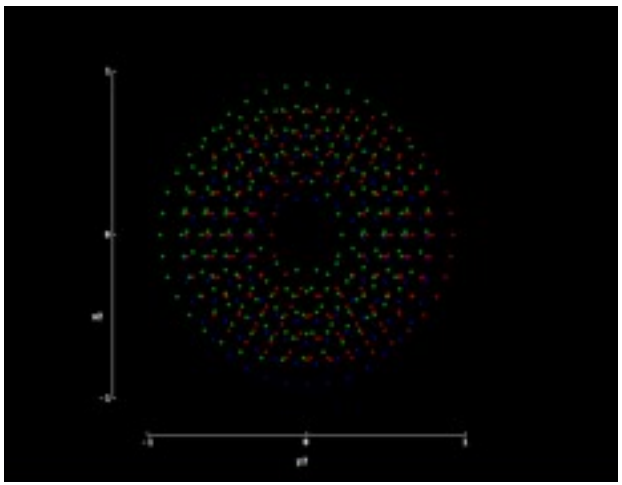


Instrument: FiberViewCam

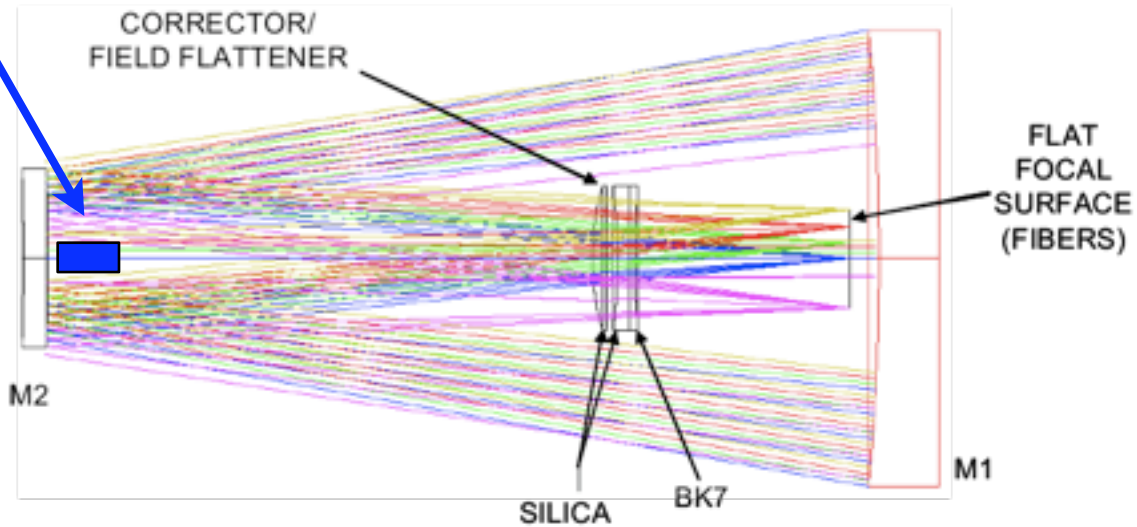
Image fibers from near M2

Calibrates positions of all the fiber "zero positions"

Back-light fibers within the spectrograph
9k x 9k camera sits in optically-unused spot near M2



Inner 40 cm of M2 unused optically



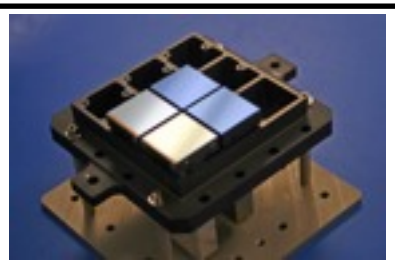
Instrument: Spectrographs x 10

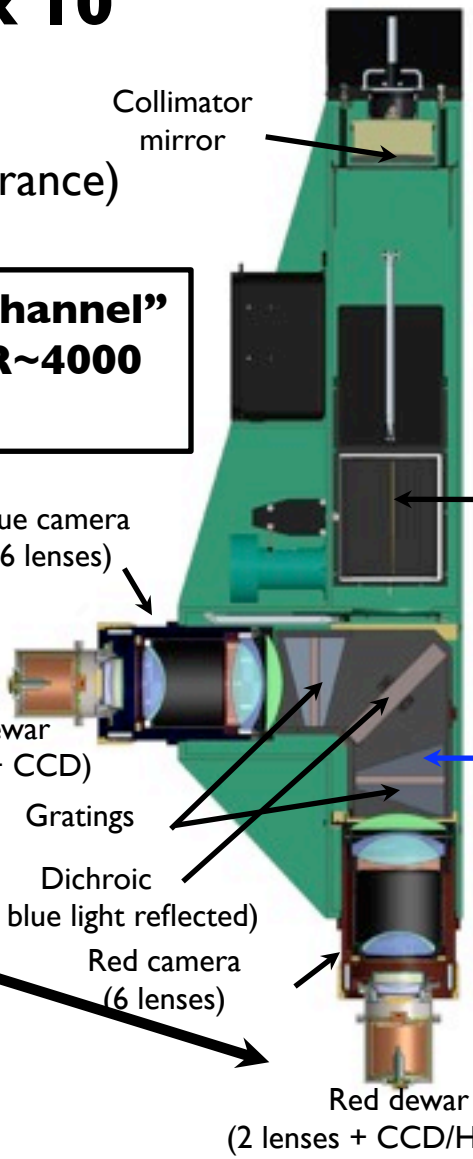
Notional design from JHU based on BOSS/WFMOS
Final design Laboratoire d'Astrophysique de Marseille (France)

Blue "QSO Lyα channel"
3400-5500 Å at R~4000
e2v CCDs

Visible "supernova channel"
5500-8000 Å at R~3500
LBNL CCDs (not shown)

Red "galaxy channel"
8000-11,300 Å at R~5000
LBNL CCDs + Teledyne HgCdTe



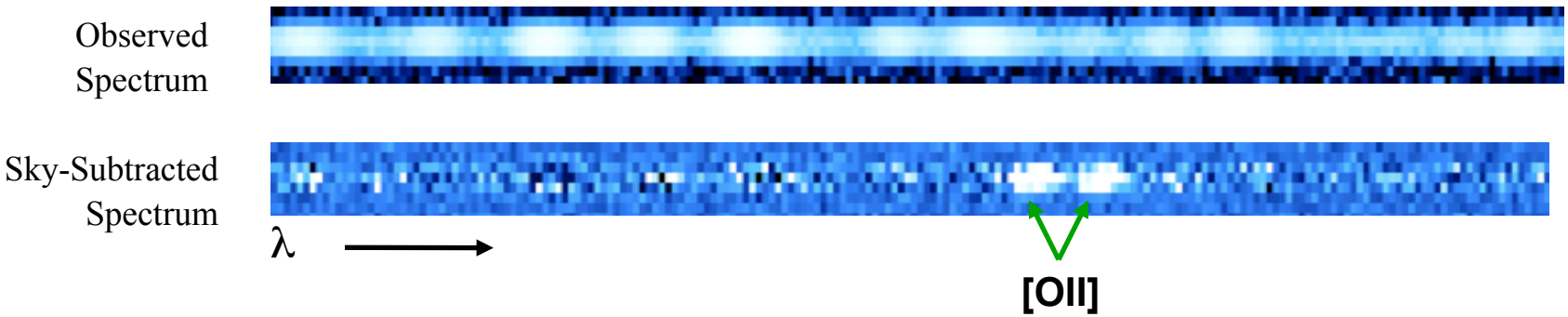


The Ground-Based Stage IV BAO Experiment

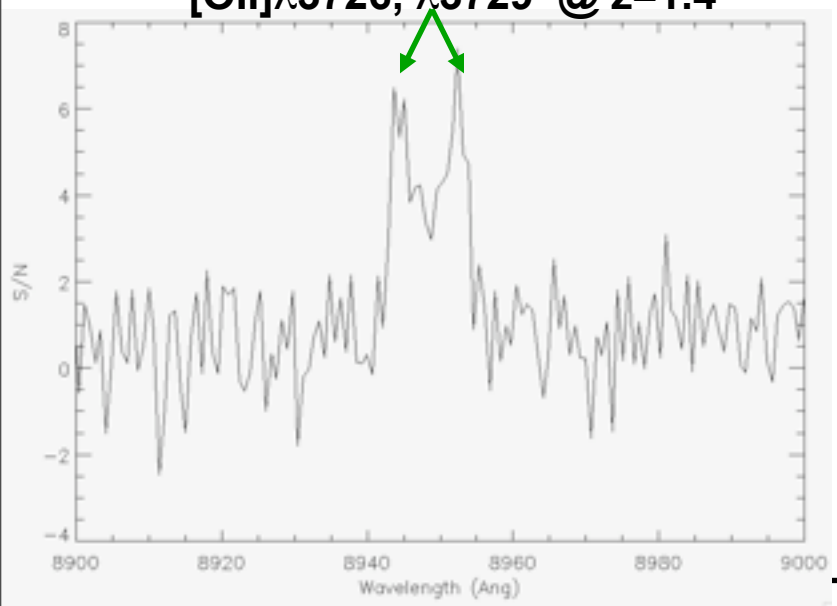
BigBOSS

Instrument: Spectrographs x 10

Instrument designed to be a "BAO spectrograph"
Detect emission-line galaxies at z=0.6→2.0



[OII]λ3726, λ3729 @ z=1.4



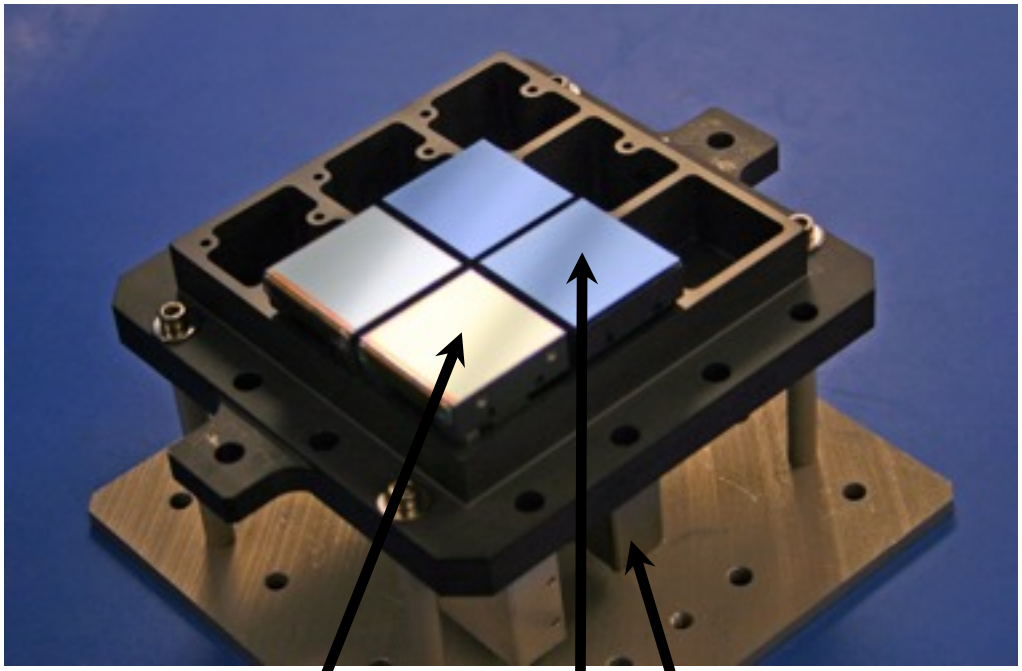
Advantage 1: R>5000 allows working between night sky lines

Advantage 2: High resolution splits the [OII] doublet

Instrument: Detectors

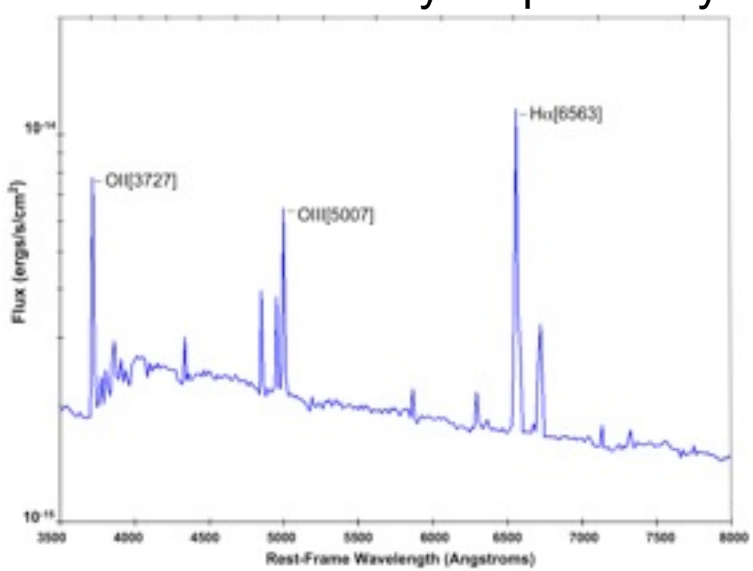
Optical+IR focal plane in red "galaxy channel"

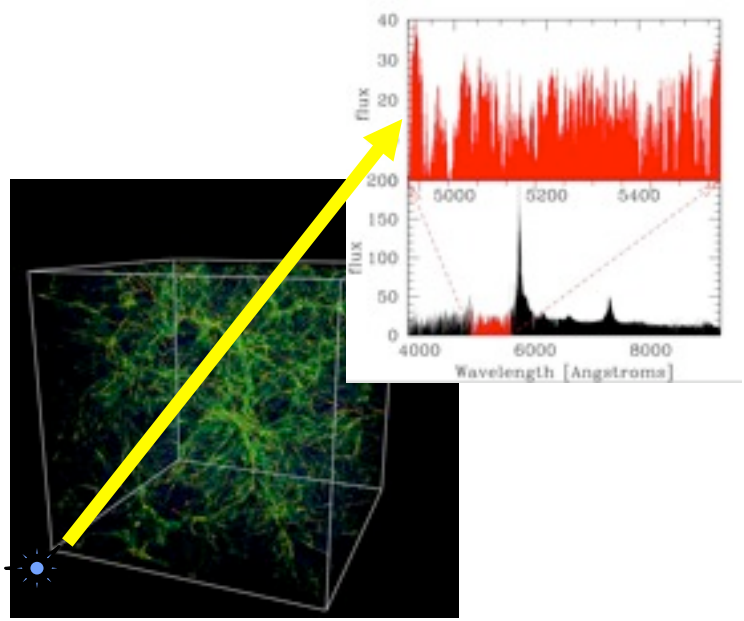
Developed by LBL Microsystems Lab for SNAP/JDEM satellite



Targets: 3 samples

- **Luminous Red Galaxies (LRGs):**
  - Selected to z<1
  - Efficient BAO tracers due to large bias
- **Emission-line galaxies:**
  - Selected 0.7<z<2.0 at source density of dn/(dz deg^2)=2000
  - Redshifts from [O II], [O III] emission lines, R~5000
- **QSOs:**
  - Selected 2<z<3.5
  - 3-D density map from Ly-alpha forest

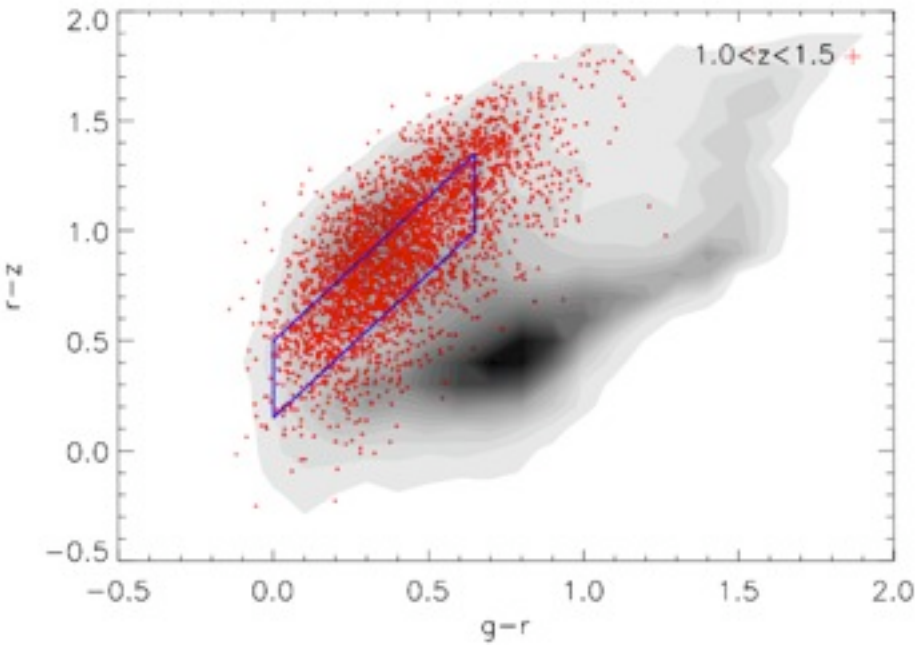




Targets: Emission-line galaxies 0.7<z<2

z<1.6 sample

grz-selected

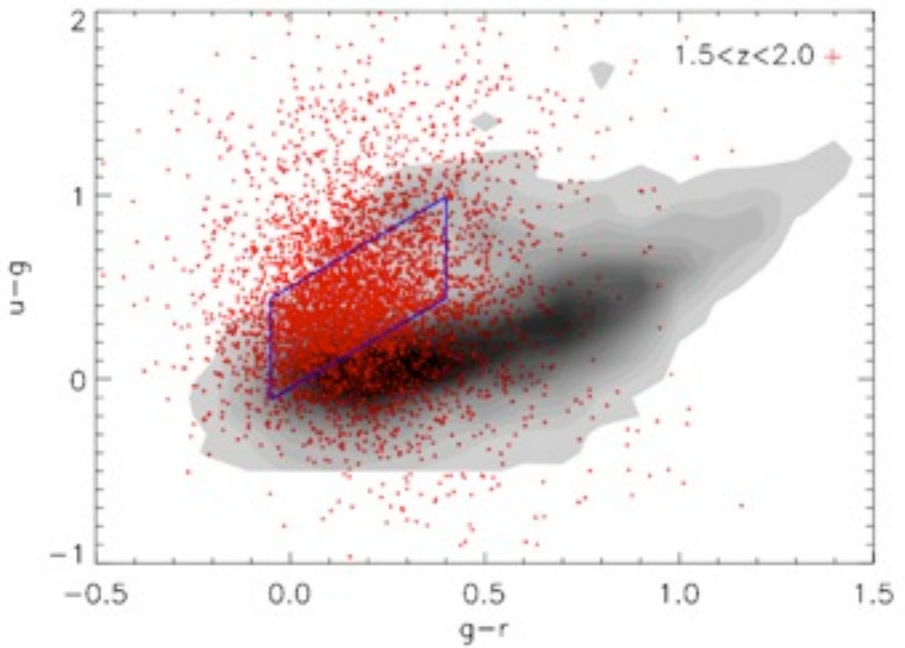


PTF *g*+*r* bands

+ PanSTARRS-1 *z*-band

1.5<z<2 sample

ugr-selected



PTF *g*+*r* bands

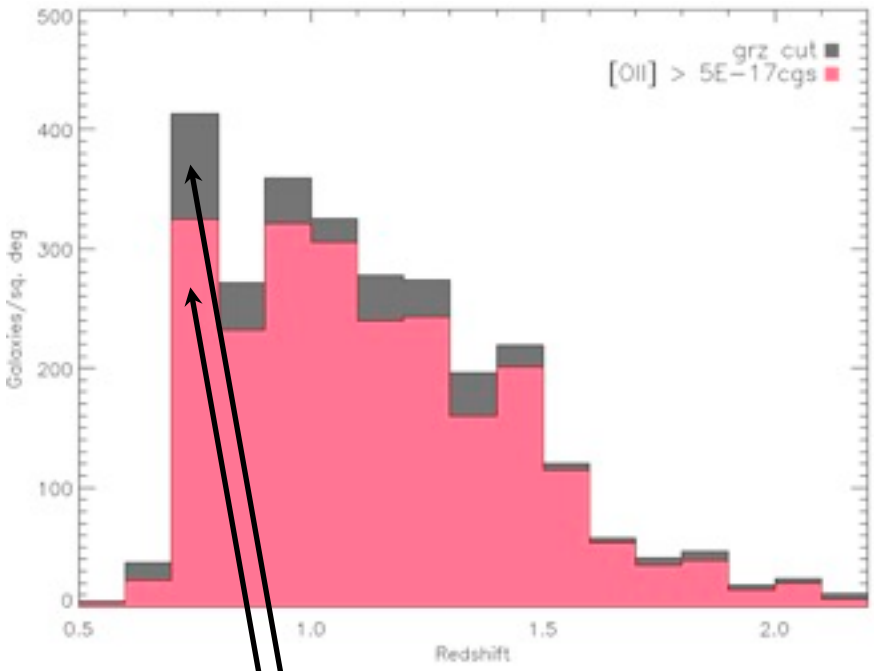
+ CFHT *u*-band (proposed)

Synthetic magnitudes are degraded using photometric errors from Palomar Transient Factory (*gr*), Pan-STARRS-1 (*iz*), and a CFHT-like survey (*u)*

Targets:
Emission-line galaxies 0.7<z<2

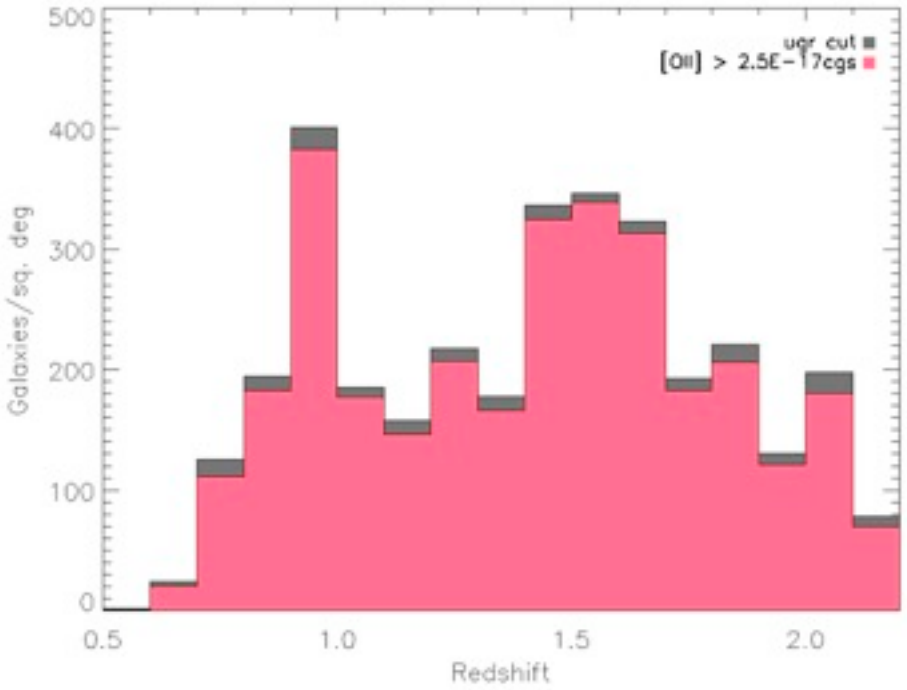
z<1.6 sample

grz-selected



1.5<z<2 sample

ugr-selected



Galaxies satisfying color-mag cuts

... and detectable [O II] emission

zCOSMOS and DEEP2 demonstrate large fraction of bright em lines at z>1

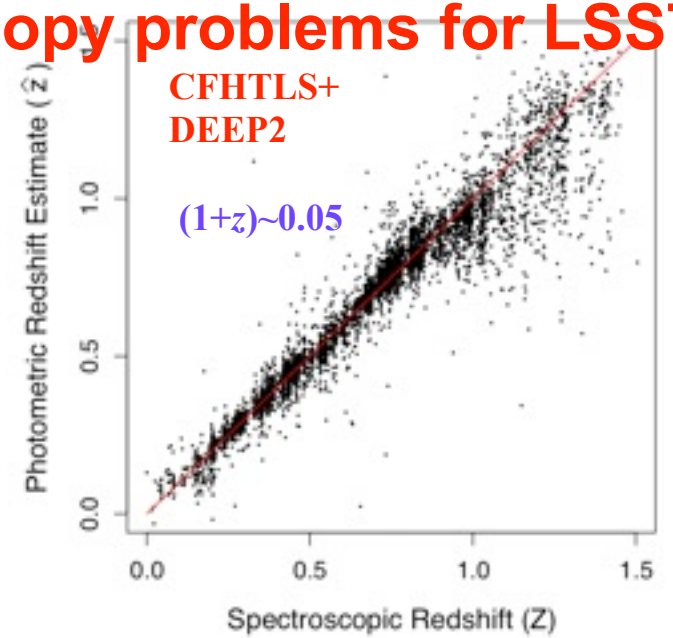
Project scope

BigBOSS instrument compares well to WFMOS

- Easier design on 4m telescope
- Smaller aperture, but high throughput (no lens couplers, etc)
- More λ coverage (340-1150 nm)
- Higher resolution for full-λ coverage (R~5000 instead of R~1500)

BigBOSS solves many spectroscopy problems for LSST

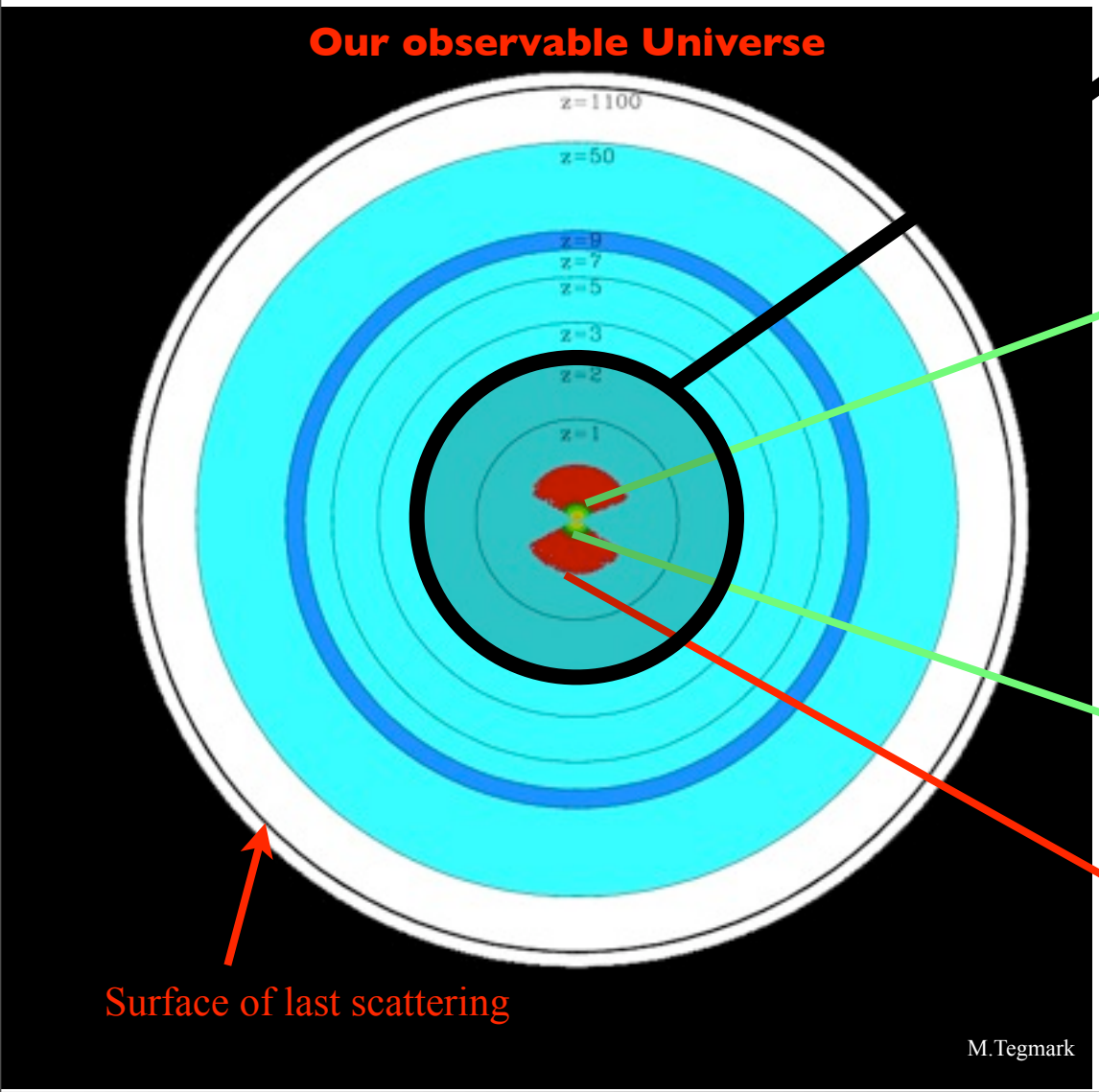
- LSST primary science:
- Redshift training for photo-z's



Freeman, Newmann et al. 2009

Large Redshift Surveys

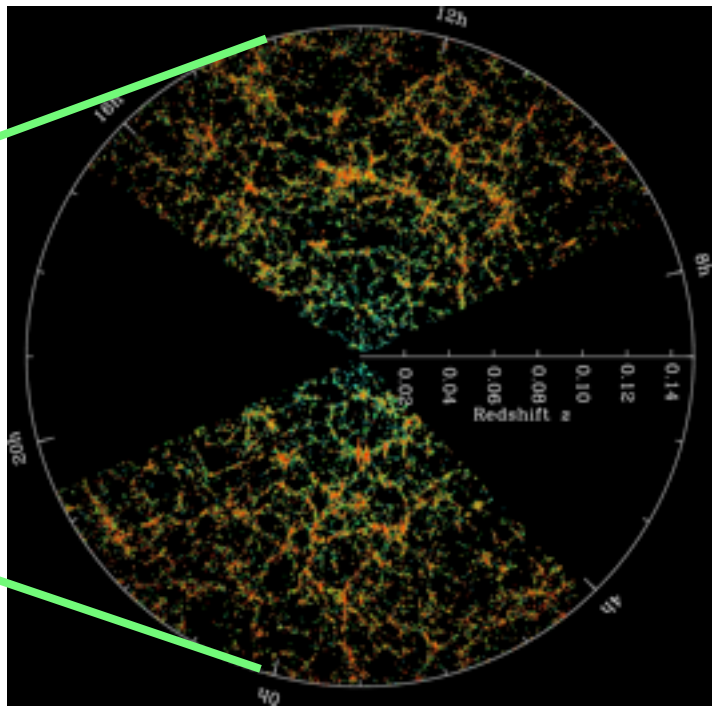
Sensitivity to new physics scales as volume -- # of modes
Galaxy maps can greatly exceeds information content of CMB



BigBOSS galaxies

15 million linear modes!

Volume mapped by SDSS



Volume to be mapped by SDSS-III (ca. 2015)

400,000 linear modes

BigBOSS: The Stage IV BAO Experiment Conclusions

- ***A "Stage-IV" dark energy scientific program from the ground***
  - "BAO spectrograph" is optimized for redshift-finding
    - $0 < z < 1.0$ from absorption-line galaxies
    - $0 < z < 2.0$ from emission-line galaxies
    - $1.8 < z < 3.5$ from QSO LyA forest
  - Up to 50 million galaxies in 10 years
    - SDSS BAO discovery was 60,000 galaxies
    - BOSS will have 1,500,000 galaxies, $0.3 < z < 0.7$
    - JDEM uses a blind search and finds more galaxies, but not better figure-of-mert
- ***Physics beyond the standard model***
  - More linear modes than CMB maps == higher sensitivity to non-gaussianity from inflation
- ***Complementary to large imaging surveys (DES, LSST)***
  - Adds spectroscopic capability, eg. for SNe follow-up
  - Calibrates LSST photo-z's for WL
- ***Requires only 4-m telescope time***
  - North: Kitt Peak (4m)
  - South: CTIO (4m)

Extra slides

BigBOSS cosmological constraints beat CMB!

Lyman Alpha Forest: what can it do?

- **Cosmological constraints from Lyman-alpha power spectrum (with no BAO)**

	Planck	Planck + BigBOSS Lya	Planck + BigBOSS Lya + Galaxies
$\sigma(\sum m_\nu)$	0.307	0.048	0.006
$\sigma(\Omega_K)$	0.011	0.0041	0.00038
$\sigma(n_s)$	0.0034	0.0023	0.001
$\sigma(dn_s/dln(k))$	0.003	0.0028	0.0005

Courtesy from Anze Slosar

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BigBOSS inflation constraints beat CMB!

Lyman Alpha Forest: what can it do?
—Non-gaussianities in Early Universe

Berkeley Lab

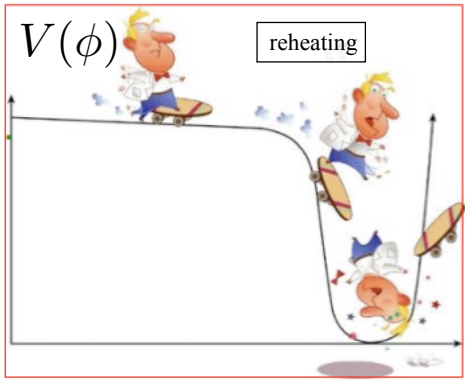
parameterize how much non-linear corrections are there to the potential

$$\Phi = \phi + f_{NL}\phi^2$$

Primordial potential (assumed to be gaussian random field)

Non-Gaussianity from Inflation

- f_{NL} ~ 0.05 canonical inflation (single field, couple of derivatives) (Maldacena 2003, Acquaviva etal 2003)
- f_{NL} ~ 0.1--100 higher order derivatives
  - DBI inflation (Alishahiha, Silverstein and Tong 2004)
  - UV cutoff (Craminelli and Cosmol, 2003)
- f_{NL} >10 curvaton models (Lyth, Ungarelli and Wands, 2003)
- f_{NL} ~100 ghost inflation (Arkani-Hamed et al., Cosmol, 2004)



← Inflation →

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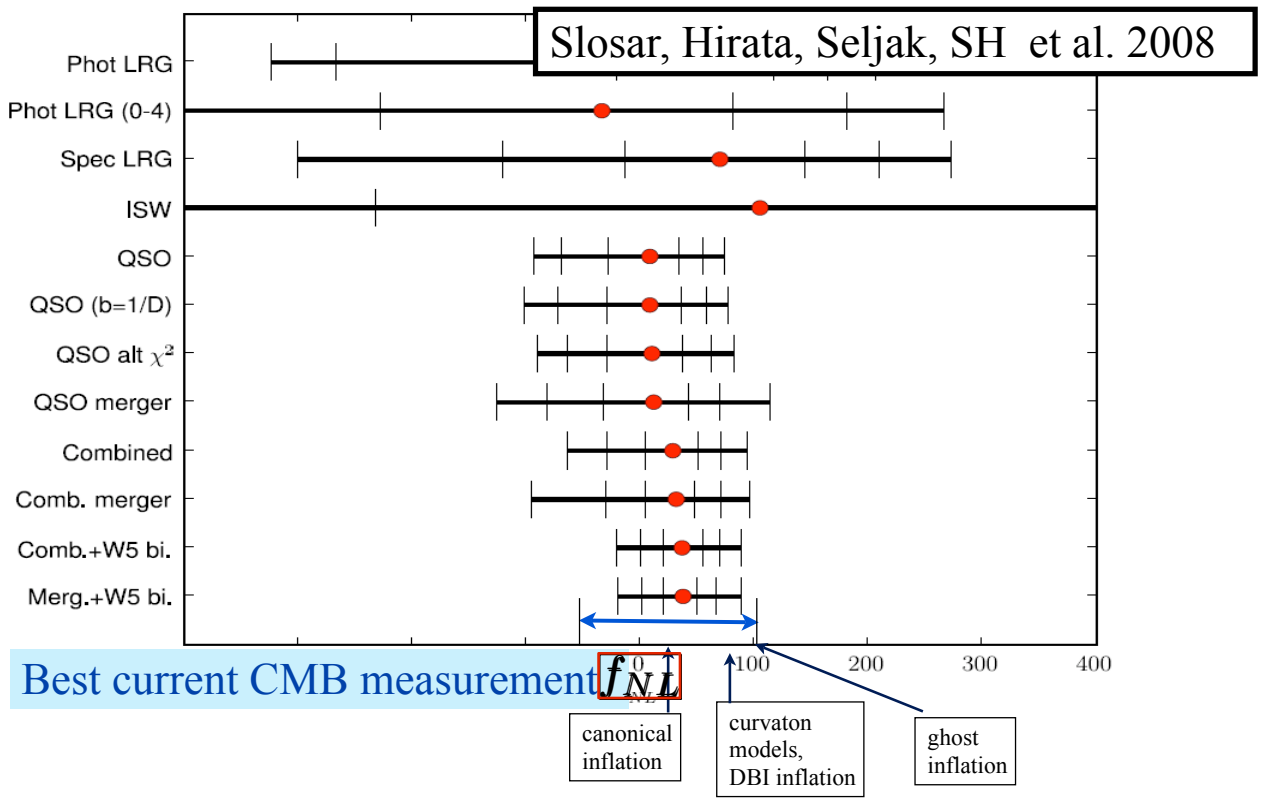
BigBOSS: The Stage IV BAO Experiment

Physics beyond the standard model

BigBOSS projected constraints f_{NL}~2

Lyman Alpha Forest: what can it do?

—Non-gaussianities in Early Universe



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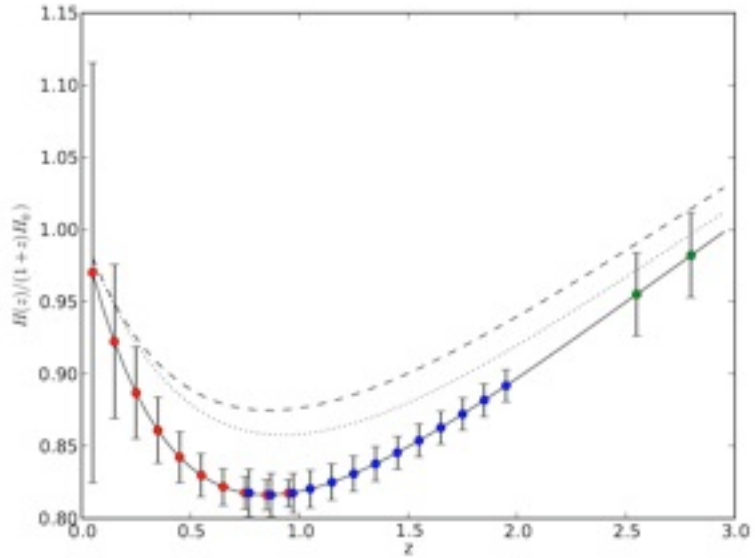
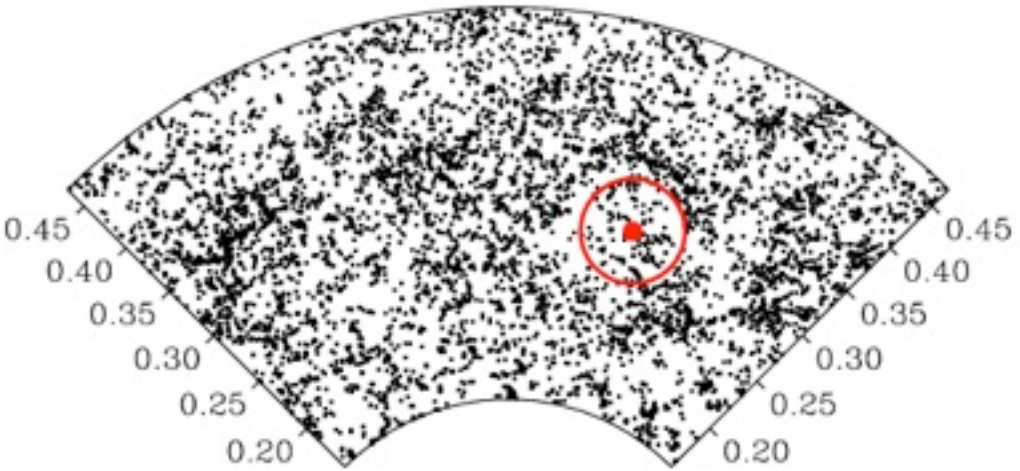
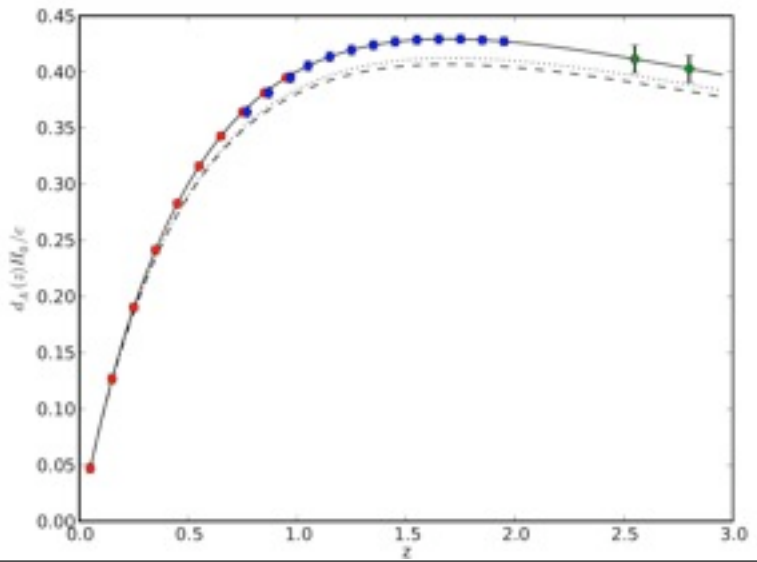
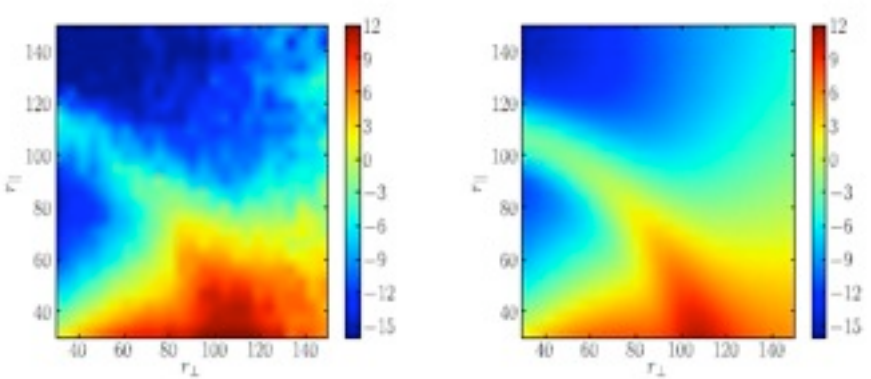
BAO:
Geometric probe of dark energy





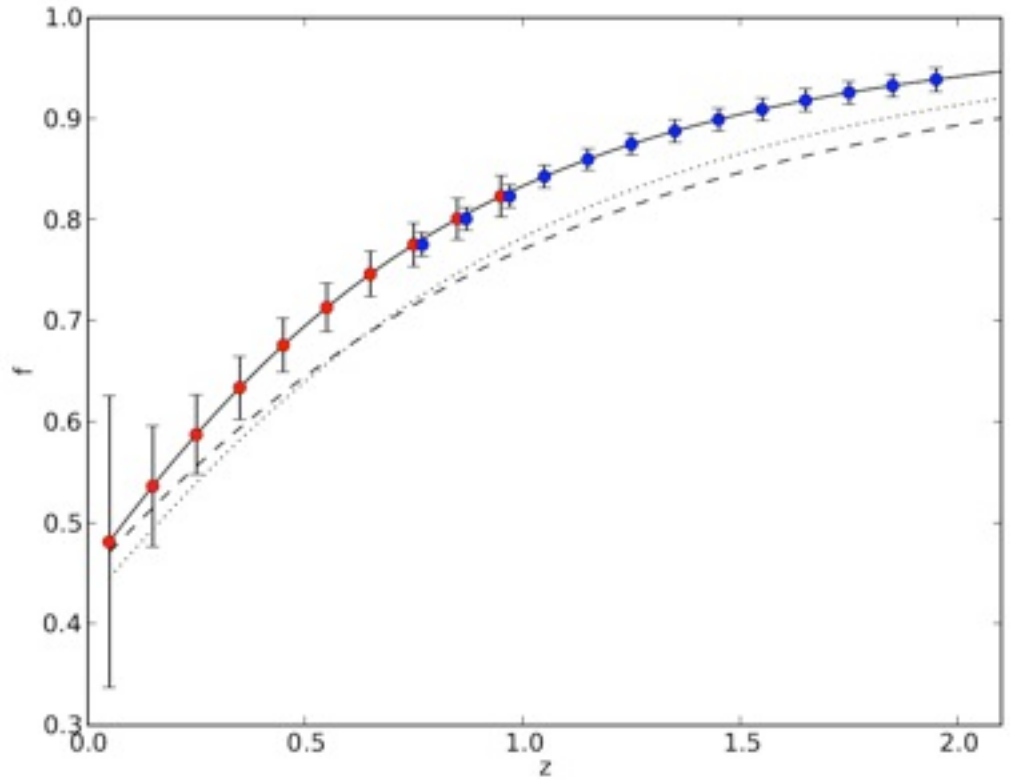
BAO scale in SDSS galaxies.

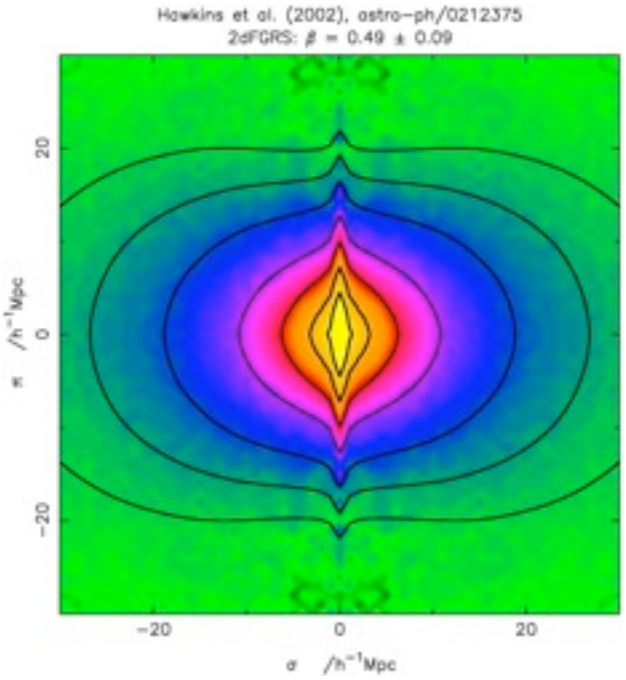




BAO in Lyman-Alpha (Slosar et al in prep.)

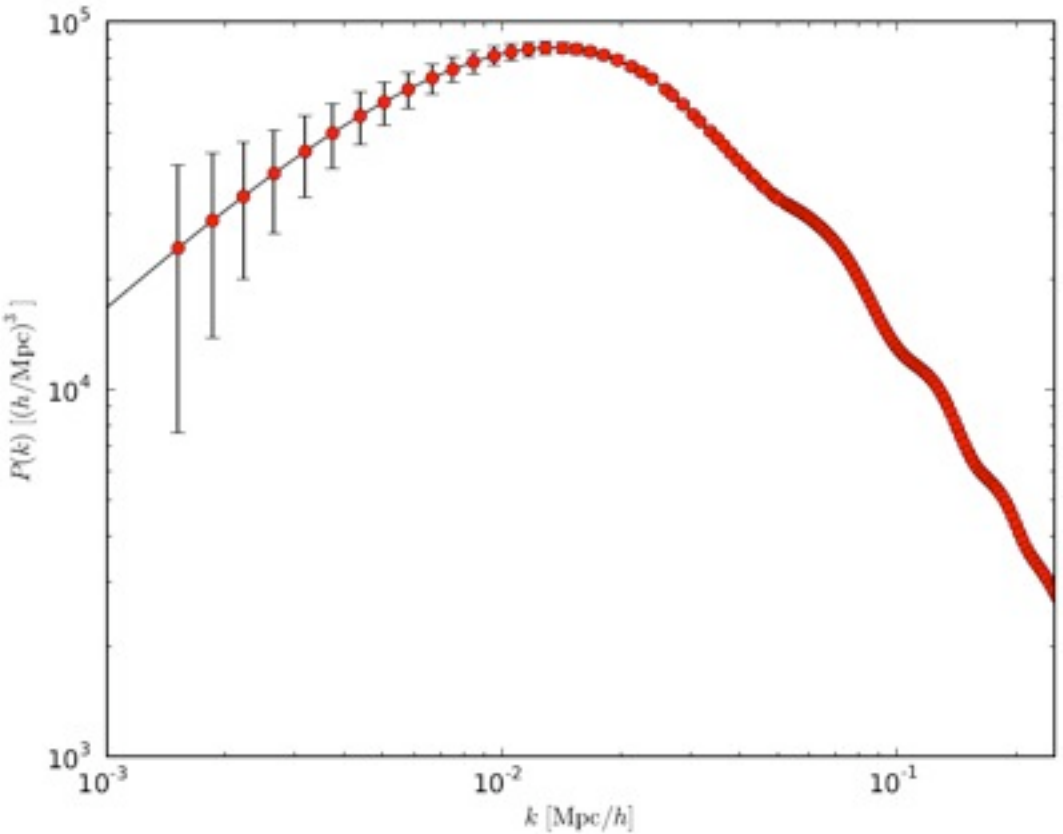
Redshift-space distortions: Gravitational probe of dark energy





- Competitive with BAO
- Relatively conservative estimates of error bars
- Probes growth of fluctuations rather than geometry

BigBOSS:
Linear power spectrum

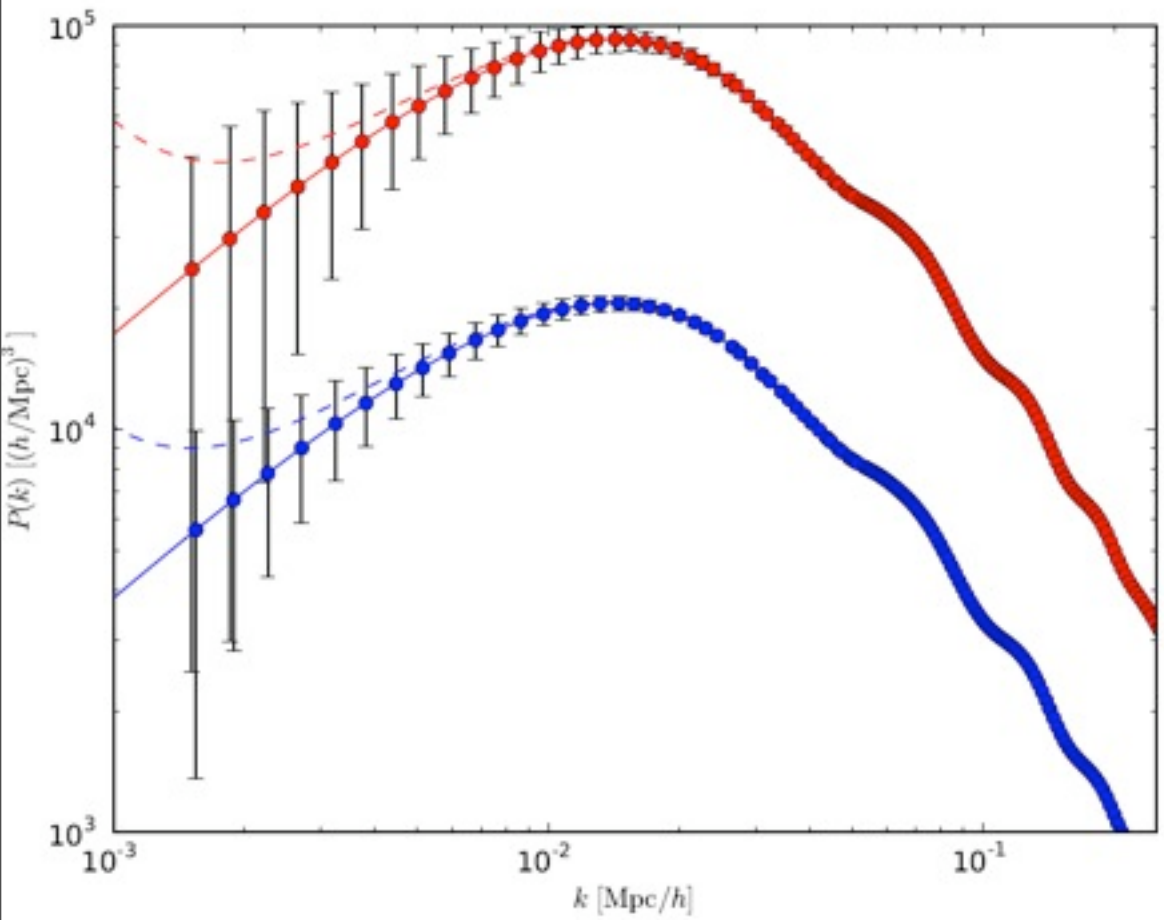


Preliminary:
Errors assume Gaussianity and no systematics

- Significant improvements in cosmological parameters from the shape of the linear power spectrum
- Guaranteed detection in several areas (N only, with Planck):

Neutrino mass	**0.019 eV** **0.018 eV for JDEM** **(current knowledge >0.05 eV)**
Number of relativistic species	**0.12** **0.11 for JDEM**
Curvature	**0.0006** **Factor 10 better than Planck** **0.0005 for JDEM**
Spectral index / running	**0.0030/0.0018** **Factor 6 better than Planck** **0.0028/0.0017 for JDEM**

BigBOSS:
Non-gaussianity and f_{NL}



- Induces scale-dependent bias
- Big Volume helps!
- Interesting region around $f_{NL} = 1$
- Dashed lines predictions for $f_{NL} = 5$
- Systematics controlled by having multiple samples with different biases
- Selection function under control

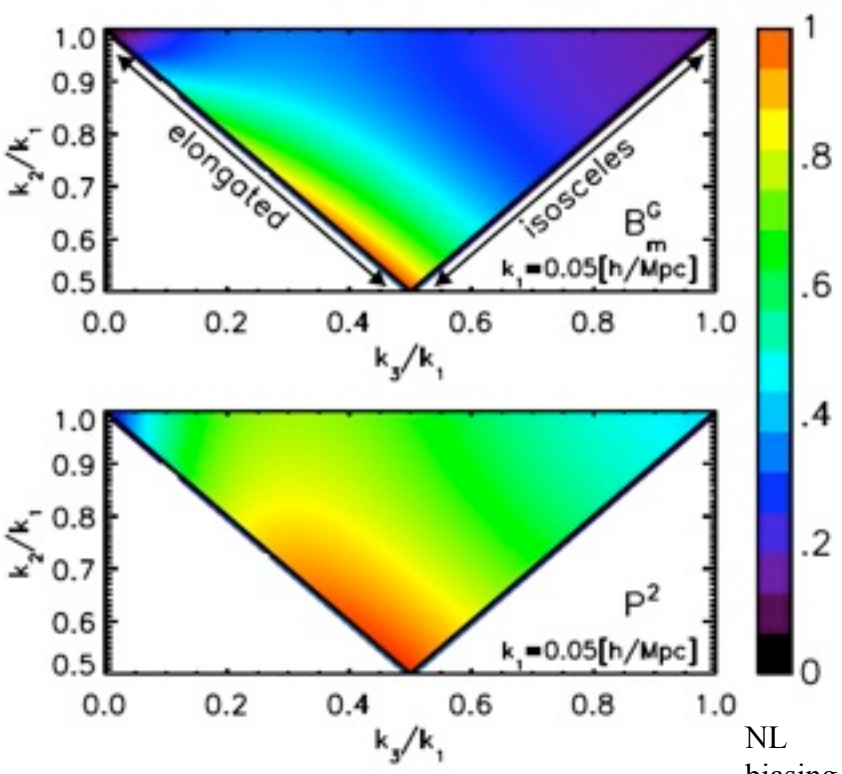
BigBOSS allows systematics checks w/ multiple samples

JDEM-BAO satellite lacks this

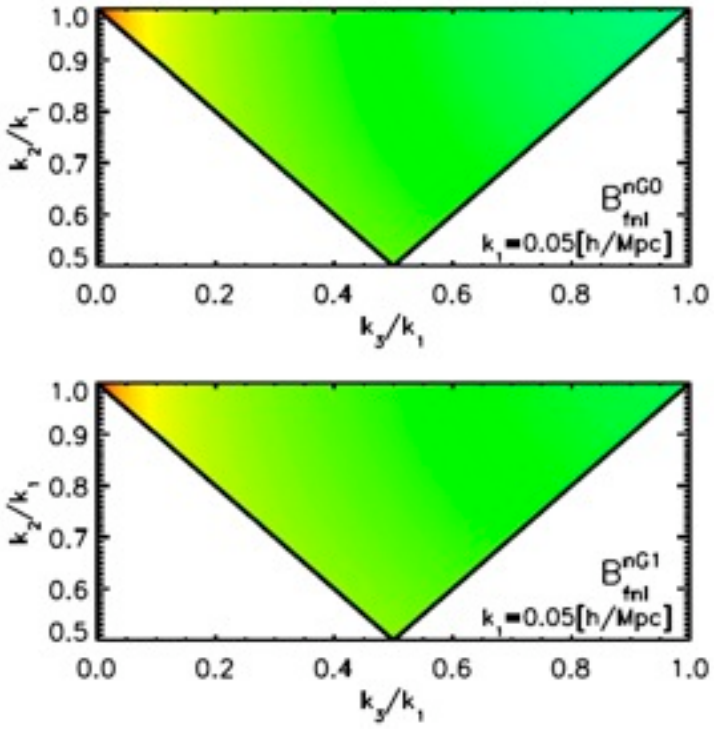
BigBOSS: Bispectrum

- Has big potential, in principle:
  - Measures **GROWTH -- yet another dark energy probe**
  - Can measure more general types of non-Gaussianity
  - Large scales implies better behaved sample than e.g. SDSS
  - Different contributions separated by different triangle configurations
  - Plots from Jeong and Komatsu:

NL grav. evolut.



NL biasing



Non-Gaussianity induced