From quasars to dark energy Adventures with the clustering of luminous red galaxies

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Where we are headed....

The two sides of galaxy clustering:

- Small scales :
  - Probe the relationship between dark matter and galaxies
  - Constraints on models of galaxy formation
- Large scales :
  - Constrain cosmology
  - Dark Energy : Baryon Acoustic Oscillations
  - Shape of the galaxy power spectrum

Outline

Outline

The Backstory

- Large photometric surveys starting (PanSTARRS, DES)
- What/ How much clustering science can one do?
- Good photo-z's only available for particular populations
  - Bootstrap off these populations
  - *Demonstrate with QSOs today*
- Brute force statistics

How to think about clustering

- Old picture : galaxies Poisson sample density field
- New picture : galaxies populate dark matter halos
- Small scales - clustering determined by how galaxies populate DM halos - 1 halo
- Large scales - clustering determined by halo clustering (weighted by number of galaxies) - 2 halo

Why LRGs?

- Old elliptical systems, with prominent 4000 Å breaks.
- Bright end of luminosity function
- Well characterized color-redshift relations

implies

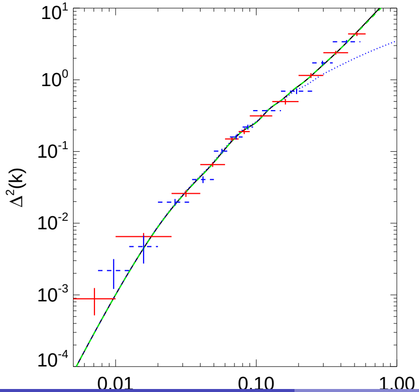
- Probes large volumes
- Ease of selection
- Accurate, well-characterized photometric redshifts (NP, Budavari, et al, 2005)

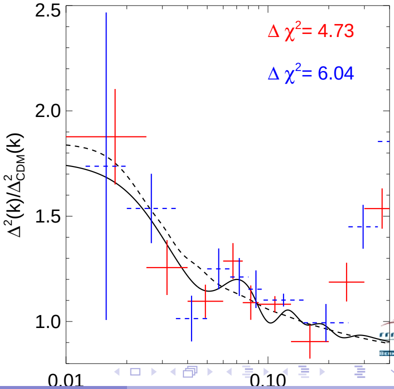
- Photometrically selected LRGs, $0.2 < z < 0.6$, $\sigma_z = 0.03$
- $\Delta z = 0.05$

LSS with LRGs

NP, Schlegel, et al, 2007

- 5.5σ detection of power for $k < 0.02h/\mathrm{Mpc}$
- 2.5σ evidence for BAO using a photometric survey

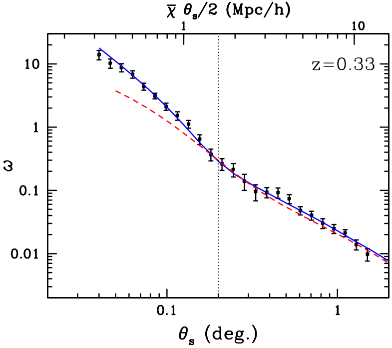




Small-Scale Clustering

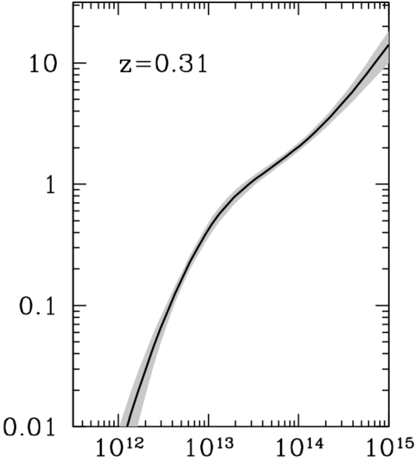
NP, White, Norberg, Porciani, 2008, arXiv:0802.2105

- Measure the angular correlation function.
- Use photo-z distribution to relate to 3D correlation function
- Transition from 1-halo to 2-halo



Small-Scale Clustering of LRGs

- Measure the angular correlation function.
- Use photo-z distribution to relate to 3D correlation function
- Transition from 1-halo to 2-halo
- $N \sim 1$ @ $M \sim 10^{13} M_{\odot}$
- Generate mock catalogs; use to interpret clustering measurements

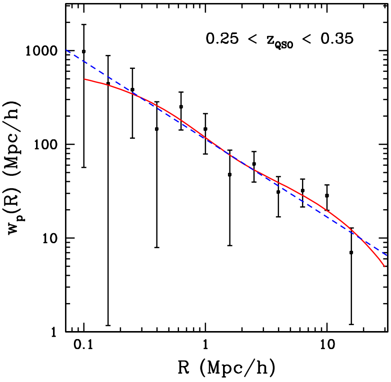


LRGs around Quasars

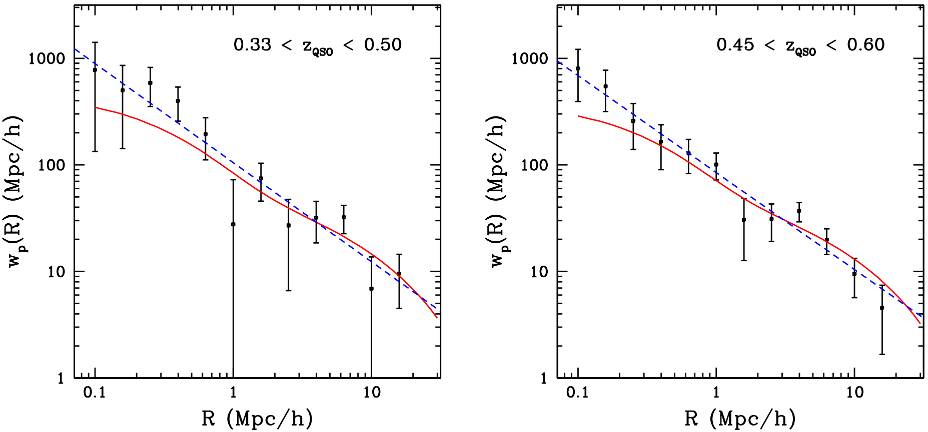
QSOs important piece of models of galaxy evolution

NP, White, Norberg, Porciani, 2008, arXiv:0802.2105

- QSOs in SDSS DR5; $z < 0.6$, $L > L_\star$
- Measure # photometric LRGs around QSOs in angular annuli over background
- Use quasar redshifts to relate angles to physical radii
- QSO-LRG correlations consistent with a power law
- $b_{QSO} = 1.09 \pm 0.15$ @ $z \sim 0.43$

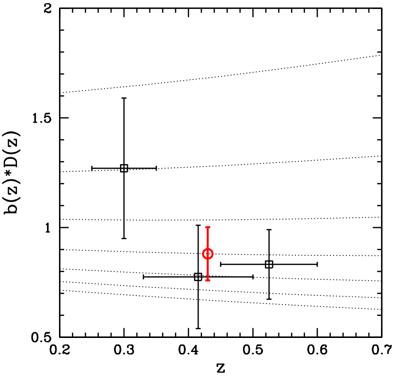


LRGs around Quasars



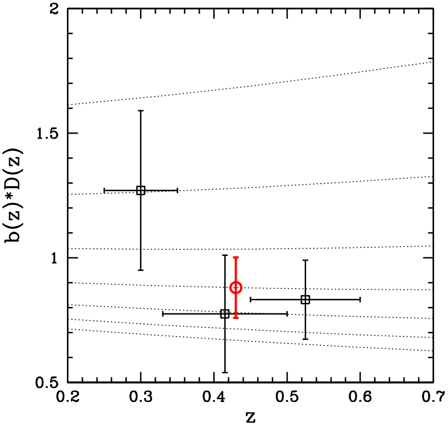
Halo masses

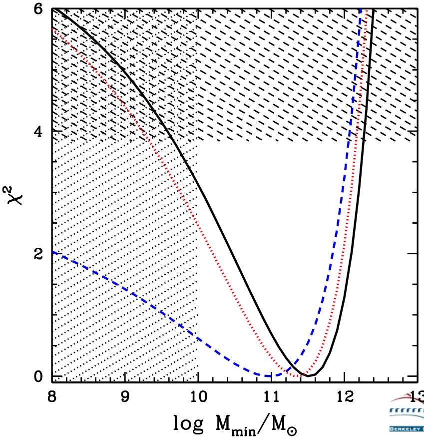
- On large scales, $\delta_g = b\delta_m$
- $$b = \bar{n}^{-1} \int dM_h \frac{dn_h}{dM} N_{QSO}(M_h) b_h(M)$$
- Halo bias asymptotes to ~ 0.5 at low masses, rapidly increases for high masses
- Asymmetric halo mass constraints
- $M \sim 10^{12} M_{\odot}/h$



Halo masses

- Upper limit on M_h, $\langle M_h \rangle \sim 10^{12} M_\odot / h$
- Robust to halo occupations





What are the quasar hosts?

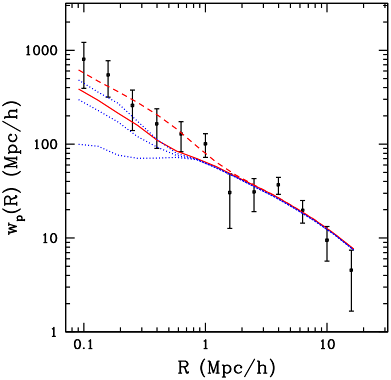
- Assume quasars are a random sampling of an underlying population
- If the host population is a luminosity-threshold sample, $L \sim 0.1 L_{\star}$
- Dependent on how one populates halos
- Tension between low bias and low number densities; possible to live in brighter hosts if we assume two quasar populations.

Duty cycles, lifetimes, etc...

- Infer other properties of quasars
- Duty cycles $< \mathcal{O}(10^{-3})$
- $t_{QSO} < 10^7 yr$; broadly consistent with $z \sim 2$
- Using $M_{\rm bh} - M_{\rm halo}$, $M_{\rm bh} \sim 10^7 - 10^9 M_\odot$
- $L/L_{\rm edd} \sim 0.01 - 1$
- All "factor of few" estimates; depends on exact assumptions made.

Interpreting small scales

- $\langle M \rangle_{\rm QSO} \sim 10^{12} M_\odot$, $\langle M \rangle_{\rm LRG} \sim 10^{13} M_\odot$
- To match small scale clustering, quasars must occupy broad mass range
- Small scales rules out quasars only at the center of halos, requires $> 25\%$ satellite fraction
- Two populations of quasars - centers at low masses, satellites at high masses?
- No excess seen at small scales



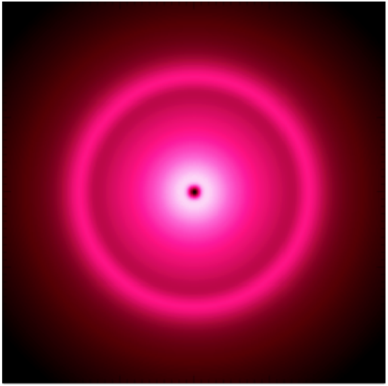
QSOs in summary

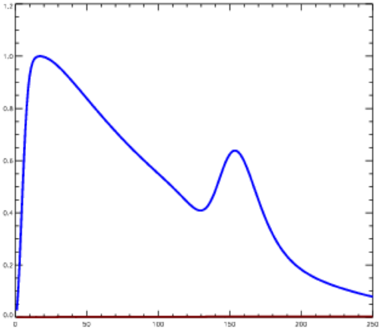
- $b_Q = 1.09 \pm 0.15$
- $M_h \sim 10^{12} M_\odot$, but also must occupy more massive halos
- Lifetimes $\sim 10^7 \mathrm{yr}$
- No evolution from $z \sim 2$
- $> 25\%$ must be satellites

Outline

A BAO cartoon

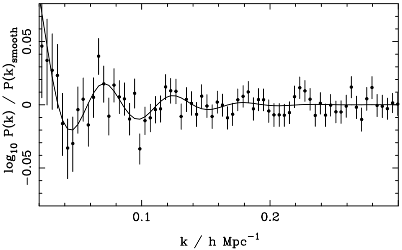
Standard ruler imprinted in the early Universe





BOSS : A next generation BAO experiment

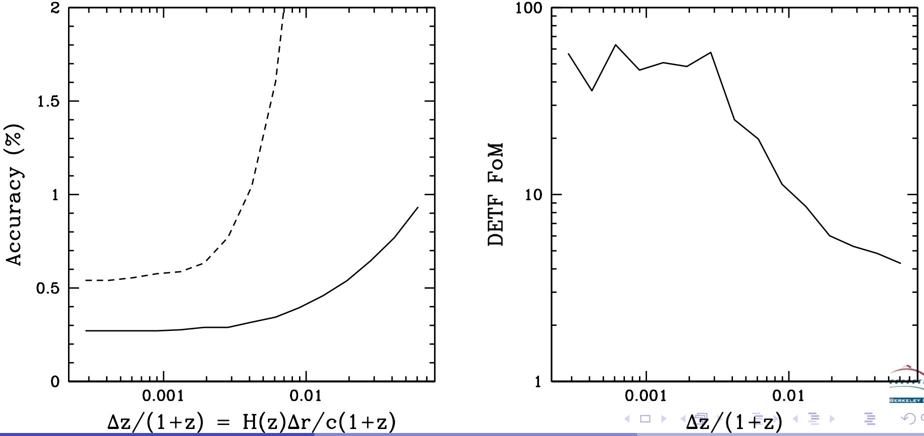
- How to do a precision $z < 1$ BAO expt.?
- After SDSS, then what?



Percival et al, 2006

Photometric vs Spectroscopic

- $S \sim P \times 5$
- Reconstruction not possible for photometric surveys



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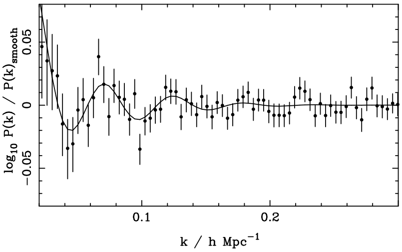


Percival et al, 2006

- SDSS imaging detects red galaxies to $z \sim 0.8$ (2SLAQ, AGES)
- The SDSS spectrograph still is one of the best wide field MOS.

BOSS in overview

- Part of SDSS-3
- Ω = 10,000 deg^2
- Fill in SDSS stripes in the south; 8500deg^2 in North, 2500deg^2 in South
- LRGs : $z \sim 0.1 - 0.7$
- QSOs (Lyman-α forest) : $z \sim 2.3 - 3.3$
- 1% d_A, 2% H at $z \sim 0.35, 0.6$
- 1.5% d_A, H at $z \sim 2.5$
- Leverage existing hardware/software where possible
- PI : David Schlegel; Director (SDSS-3) : Daniel Eisenstein

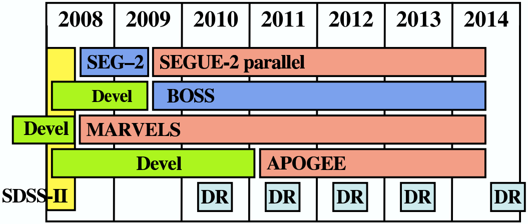
BOSS : A brief history

July 2006	Competitive proposal to use (upgraded) SDSS telescope for next-generation BAO experiment
Nov 2006	BOSS proposal selected (from 7) for all dark+grey time for 5 of 6 years
Nov 2006	First BOSS collaboration meeting (NYU)
Feb 2007	DOE R&D proposal for upgrading SDSS spectroscopic system
Oct 2007	Approval from Sloan foundation
2007 -	Funding proposals in to NSF and DOE
2009-2014	BOSS spectroscopic survey at APO

http://www.sdss3.org

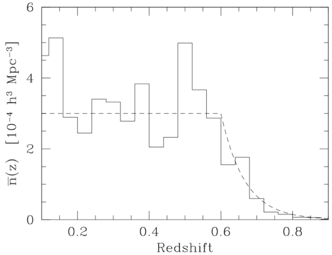
BOSS : As part of SDSS-3

- *SEGUE-2* : Kinematic and chemical structure from 350,000 stars in the outer Galaxy.
- *APOGEE* : High resolution IR spectroscopy of stars in the Galactic bulge, bar and disk.
- *MARVELS* : Radial velocity planet search around 11,000 stars
- **BOSS** : BAO with 1.5 million LRGs ($z < 0.7$) and 160,000 QSOs ($2.3 < z < 3.3$)



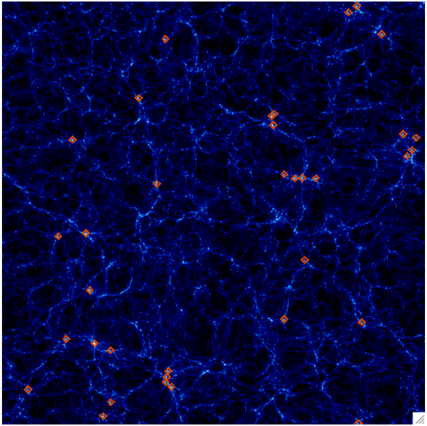
LRGs

- Targeting based on SDSS *gri* photometry
  - $i < 20$
  - Experience from SDSS, 2SLAQ, AGES
- $\sim 150/\mathrm{deg}^2$, $\bar{n} \sim 3 \times 10^{-4} (h/\mathrm{Mpc})^3$
- Sample similar to photometric samples analyzed in NP et al (2007), Blake et al (2007).
- Bias passively evolving; $b(z)D(z) \sim 1.7$ ($\sigma_8 = 0.8$)
- Small-scale clustering well understood in terms of HODs.



LRGs as tracers of LSS

A slice 500 h^{-1} Mpc across and 10 h^{-1} Mpc thick.



SDSS, $z \sim 0.5$

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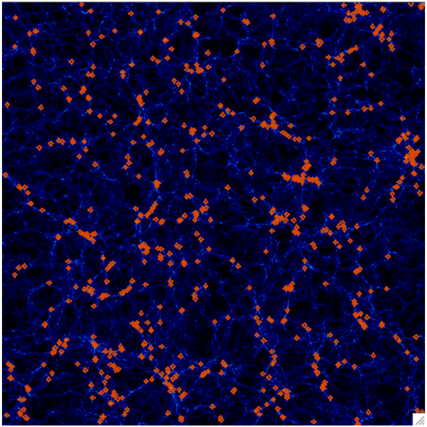


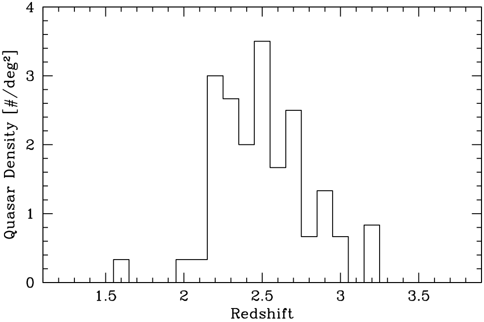
BOSS, $z \sim 0.5$

LRG forecasts

- Fisher matrix analysis
- Marginalize over shape information, only use acoustic signature. Note that this is conservative!
- $V_{eff} \sim 5(\mathrm{Gpc}/h)^3$
- Measure d_A and H to 1 and 1.5% at $z \sim 0.35, 0.6$

QSOs

- 8000 deg^2
- $g = 22$
- 20/deg^2
- Selected based on SDSS colors/ variability if available

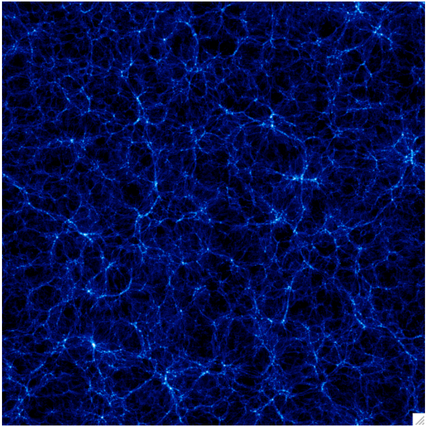


McDonald and Eisenstein, 2006

BAO with QSOs : A cartoon

Reconstructing the 3D density field from skewers

Not to scale!



DM

BAO with QSOs : A cartoon

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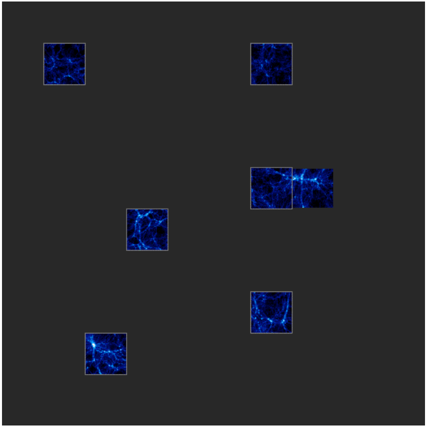

SDSS

BAO with QSOs : A cartoon

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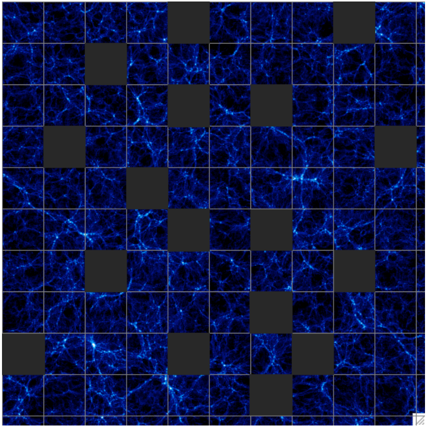
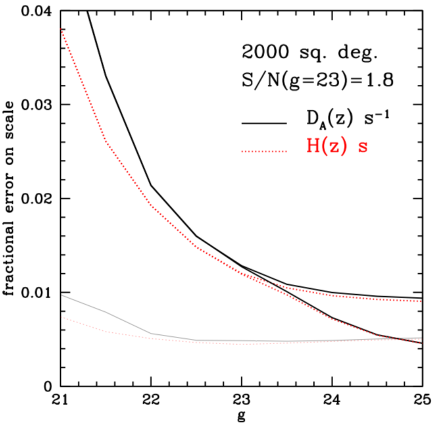


BOSS

QSO forecasts

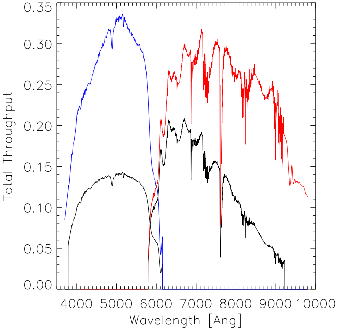
- 8000 deg^2
- $g = 22$
- 1.5% in d_A, H
- Comparable to other high-z surveys, but with 2.5m telescope

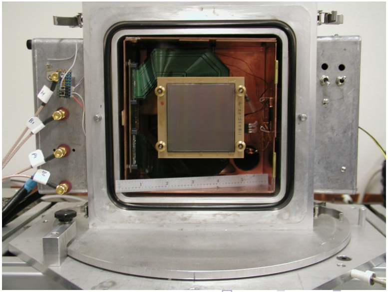


McDonald and Eisenstein, 2006

Hardware upgrades

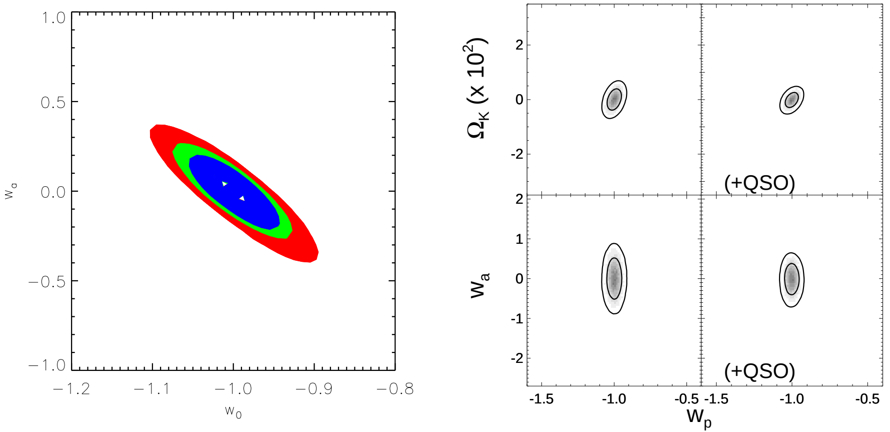
- Replace 640$\times$ 3 arcsec fibers with 1000$\times$ 2 arcsec fibers.
- Replace existing red/blue CCDs with (larger & better) LBL/Fairchild/E2V CCDs.
- Replace existing gratings to VPH grisms.
- Increase wavelength range to 3700 - 9800 Å.





Dark Energy Constraints

DETF FoM = 122 (BOSS BAO), 257 (+P(k)), 479 (+WL+SN+CL)



BOSS in Context

Compared with other spectroscopic BAO surveys

Project	Redshift	Area (deg^2)	$\bar{n}(\times 10^{-4})(\mathrm{Mpc}/h)^3$	FoM
Stage II	-	-	-	53
WiggleZ	0.4-1.0	1000	3.0	67
HETDEX	2.0-4.0	350	3.6	70
WFMOS	0.5-1.3	2000	5	
	2.3-3.3	300	"	95
BOSS LRG	0.1-0.8	10000	3.0	**86**
+ QSO	2.0-3.0	8000	-	**122**
+ Stage III	-	-	-	**331**

More Cosmology

- Precision measurements of H_0 (1%), Ω_K (0.2%)
- Constrains $D(2)/D(1000)$ and $D(0.5)/D(1000)$ to 0.6% and 1% within ΛCDM
- Improved large scale structure constraints (250,000 modes with $k < 0.2$)
- Improved measurements from the Lyman-α forest
- Improved measurements of neutrino masses
- A S/N=200 measurement of ξ_{gm} from galaxy-galaxy lensing, direct probe of $D(z)$
- Constrain $f_{nl} <\sim 10$
- .....

Galaxy Formation/ Evolution

- Evolution of massive galaxies
- Improved QSO clustering measurements at $z > 2$
- Piggy-back program will double N_{QSO} with $z > 3.6$
- Synergy with next generation imaging surveys (eg. Pan-STARRS) [cross-correlation studies, galaxy-galaxy lensing]
- Serendipitous stellar studies (from QSO targeting)
- Spectroscopic detection of galactic scale strong lensing systems
- Projects we haven't thought of......

What's next for BOSS?

- *July, 2008:* SDSS-II ends, SDSS-III begins
- Complete 2000 deg^2 on imaging in the South in Fall 2008.
- Upgrade spectrographs Summer 08/09.
- LRG/QSO spectroscopy Fall 2009 - 2014
- At which point, we should know....
  - $w_p = -??.?? \pm 0.03$, $w_a = ??.?? \pm 0.28$
  - $h = 0.?? \pm 0.008$, $\Omega_K = 0.?? \pm 0.002$

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BOSS in a nutshell

- On the SDSS 2.5m telescope
- Using LRGs between z=0 to 0.7, 1% distance constraints
- Using the Lyman-α forest, z=2.3 to 3.3, 1.5% distance constraints
- Within a factor of 2 of a low-z cosmic-variance BAO measurement
- DETF FoM = 122, 331 (with Stage III)
- Lots of auxiliary science

Outline

Fin

- LRGs : A useful cosmological hammer
- Cross-correlations with QSOs used to constrain halo-QSO connection
- Generalize to other populations (e.g. galaxies)
- BOSS : A next generation baryon-oscillation survey