# Science with BOSS, the Baryon Oscillation Spectroscopic Survey

Natalie Roe, LBNL

Cosmology on the Beach

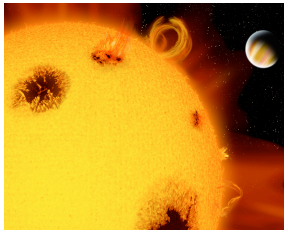
January 10, 2010

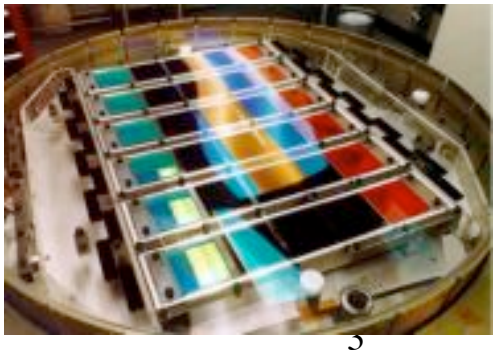
# Outline

- BOSS Overview
  - SDSS-III
  - Spectrograph upgrade
  - Survey status
- BOSS Science
  - Baryon Acoustic Oscillations
    - LRGs
    - Quasars
  - Ancillary Science
- Conclusions and Outlook

# SDSS-III and BOSS

- BOSS is the flagship survey in the third-generation SDSS-III project
  - Proposed in 2006; started in Fall 2009
  - Requested 4 years; awarded 5!
- SDSS-III has 4 new surveys to address 3 forefront topics in astrophysics:
  - **BOSS: Dark Energy & Cosmology**
  - SEGUE-II and APOGEE: Assembly of the Milky Way
  - MARVELS: Extra-solar Planets





- BOSS uses SDSS imaging data for spectroscopic target selection

# Why SDSS-III?

- The 2.5-meter Apache Point Observatory telescope remains the world's premier facility for **wide-field spectroscopy**.
  - fiber-fed spectrographs offer a huge numerical advantage, offsetting the modest telescope aperture
- Astronomy continues to benefit from **organized dedicated surveys**, a model pioneered by SDSS
  - SDSS-III leverages major existing resources: telescope, staff, imaging data, software & pipelines, public archive infrastrucuture, etc
- BOSS builds on 2 notable successes pioneered by SDSS:
  - color selection of Luminous Red Galaxies (LRGs) using SDSS imaging
  - study of features in QSO absorption spectra

# SDSS-III Collaboration

- Univ. of Arizona
- Brazilian Participation Group (ON and 4 universities) *
- Brookhaven National Lab *
- Cambridge Univ.
- *Carnegie-Mellon Univ.*
- *Case Western Univ.*
- *Fermilab*
- Univ. of Florida
- French Participation Group (APC, CEA, IAP, LAM)
- German Participation Group (AIP, MPE, MPIA, ZAH)
- Johns Hopkins Univ.
- *UC Irvine*
- *Korean Institute for Advanced Study*
- Lawrence Berkeley National Lab
- MPA Garching
- Michigan St Univ/Notre Dame/JINA
- New Mexico State Univ.
- New York Univ.
- Ohio State Univ.
- *Penn State Univ.*
- *Univ. of Pittsburgh*
- Univ. of Portsmouth
- Princeton Univ.
- *UC Santa Cruz*
- Univ. of Tokyo
- Univ. of Utah
- Vanderbilt University
- Univ. of Virginia
- Univ. of Washington
- *University of Wisconsin*
- Several other partners in negotiation

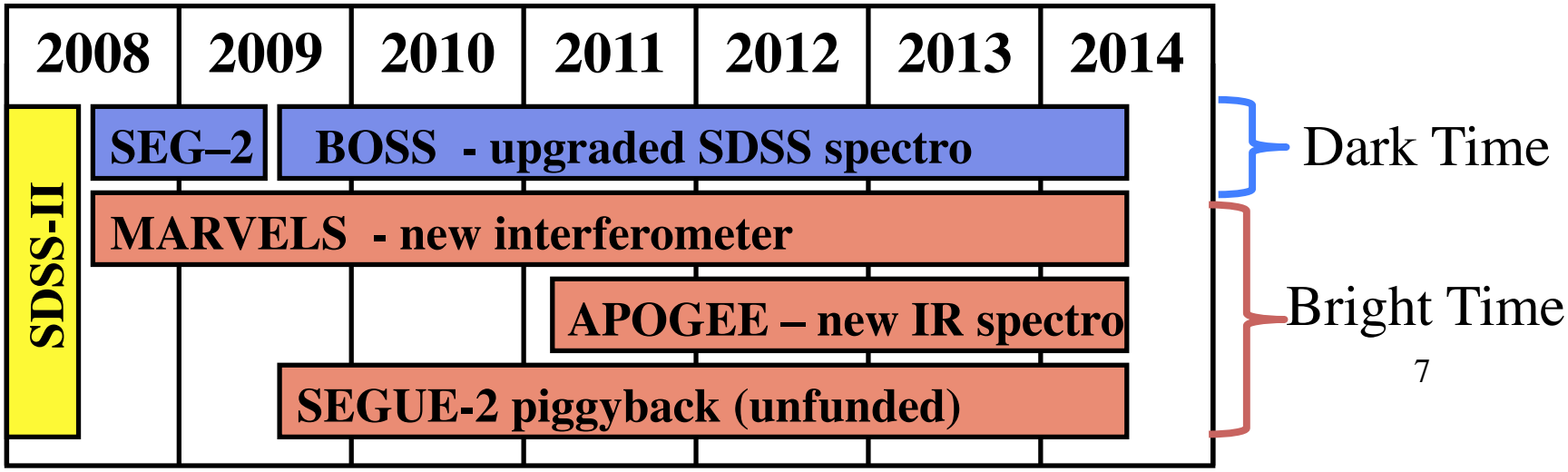
* MOU pending *Italics are for smaller associate members*

# SDSS-III Status

- Forty-two institutions have signed on!
- Supported by the Alfred P. Sloan Foundation, NSF, DOE, and institutional contributions
- SDSS-III Director is Daniel Eisenstein (U Ariz.), Spokesperson is Bob Nichol (Portsmouth)
- BOSS PI is David Schlegel, Survey Scientist Martin White, Instrument Scientist NAR (LBNL/ UCB)

# SDSS-III Status, con'd

- BOSS
  - Spectrograph upgrade complete in September 2009
  - Imaging complete in Nov 2009
  - Commissioning ~complete
  - Survey underway
- Other Programs
  - SEGUE-2: complete
  - MARVELS in 2nd year of operations
  - APOGEE spectrograph under construction



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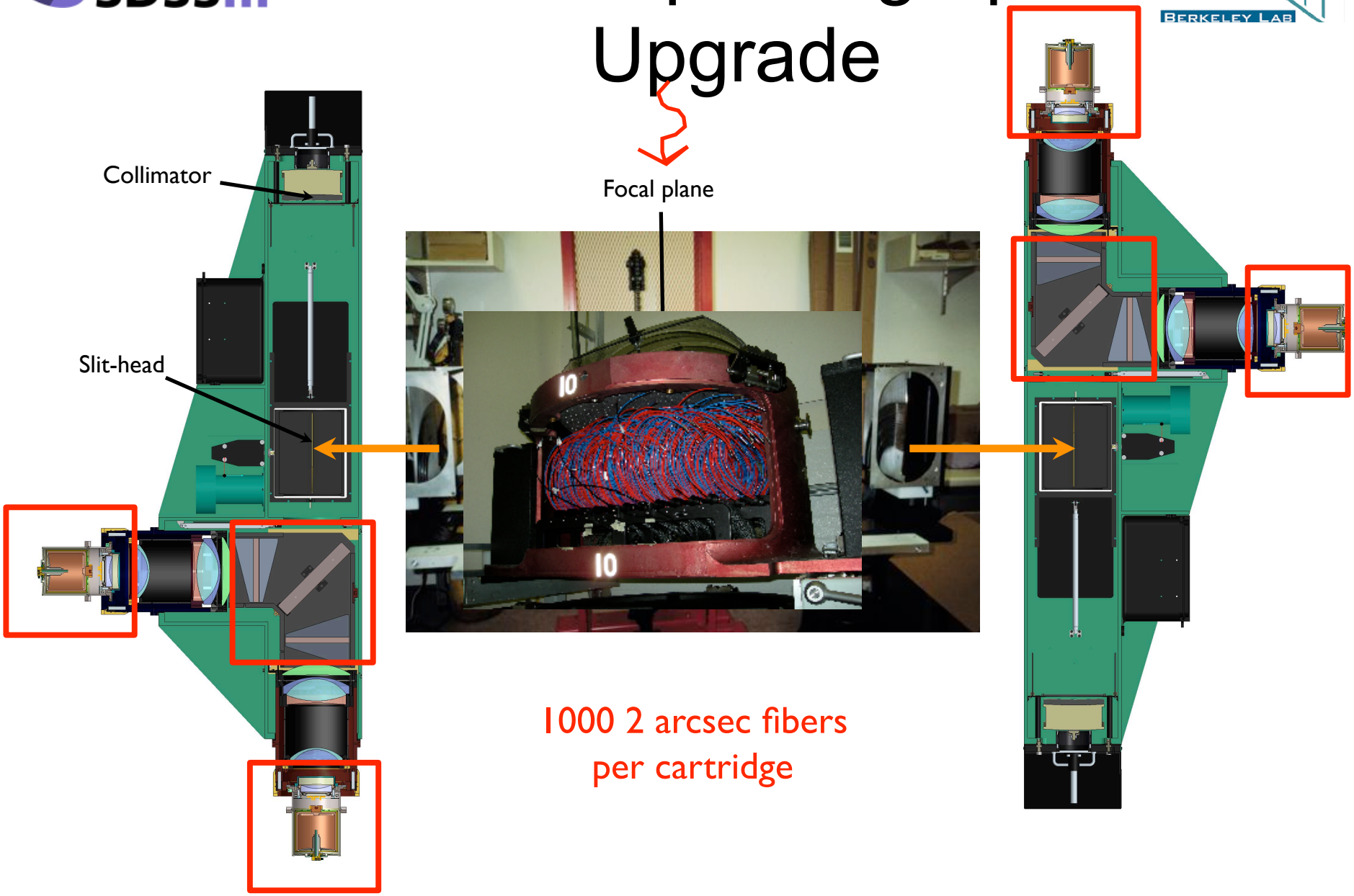
# BOSS Spectrograph Upgrade

- BOSS will observe 1.5M LRGs with $0.3 < z < 0.8$ and 150,000 QSO's with $z > 2.2$
  - x15 - 50 increase in #objects over SDSS I & II, higher z
- Dedicated 5 year spectroscopic survey
- More fibers: 640 => 1000
- Improved throughput
  - Volume Phase Holographic (VPH) gratings
  - More sensitive CCDs (higher QE)
- Broader wavelength coverage

# BOSS Spectrograph Upgrade



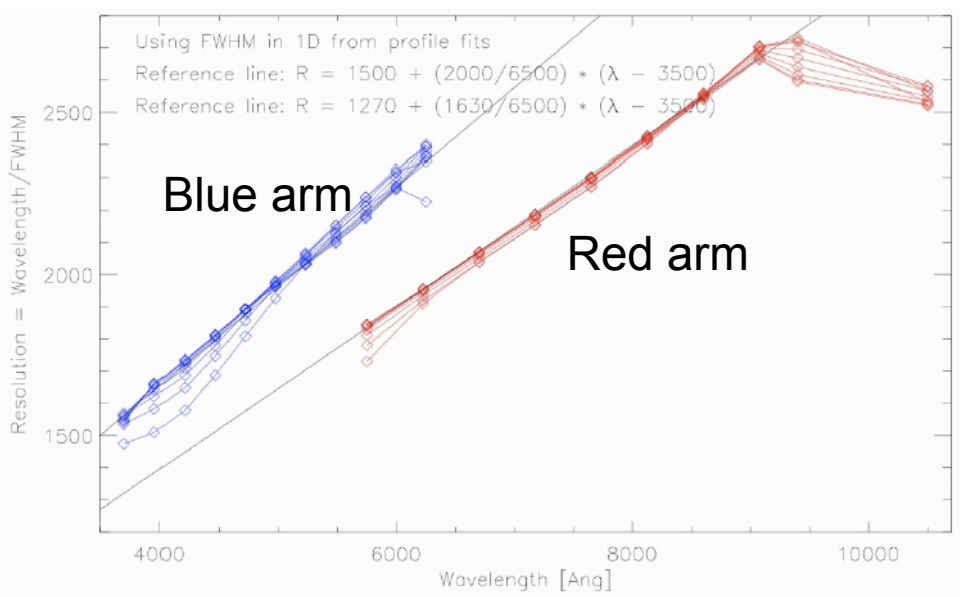

1000 2 arcsec fibers per cartridge

# SDSS and SDSS-III Spectrographs

| Parameter | SDSS | SDSS-III | Comment |
|---|---|---|---|
| Fiber output focal ratio | f/4 | f/4 | Unchanged |
| Beam diameter | 159 mm | 159 mm | " |
| Camera focal ratio | f/1.5 | f/1.5 | " |
| Blue wavelength coverage (nm) | 383 - 630 | 360 - 650 | Extended in blue and red, and |
| Red wavelength coverage (nm) | 570 - 922 | 550 - 1050 | better overlap to avoid dips |
| Number of fibers | 640 | 1000 | 50% increase |
| Fiber diameter | 160 um/ 3 asec | 120 um/2 asec | Reduced sky contamination |
| Fiber spacing on slit head | 390 um | 260 um | Larger gaps every 20 fibers |
| Spectrum spacing on detector | 6.1 pixels | 6.5 pixels | |
| CCD format | 2048x2048, 24 um pixels | 4096x4096, 15 um pixels | e2v CCDs in blue, fully depleted LBNL CCDs in red |
| Resolution element (FWHM) | <3 pixels | 3 pixels | Critically sampled |
| Resolution ($\lambda/\Delta\lambda$) | ~1800 | 1500-2700 | |

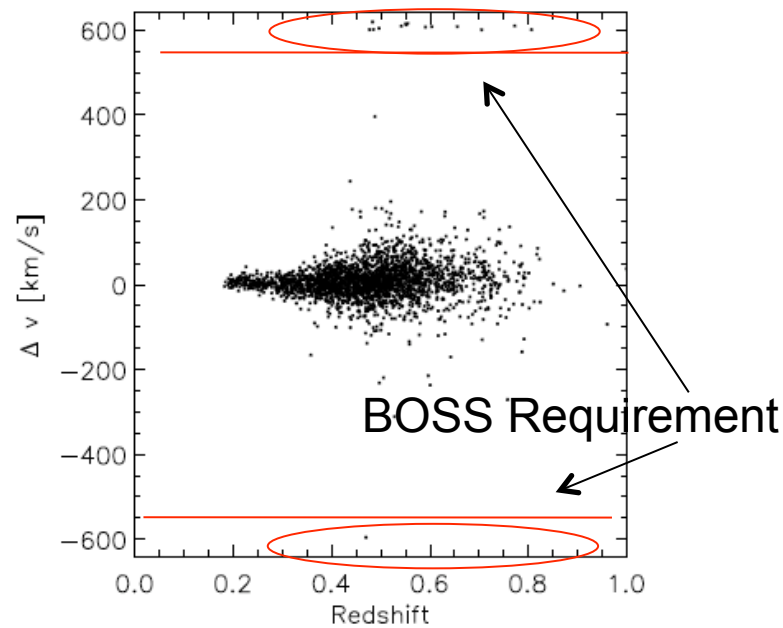
# BOSS Resolution

$\lambda/\Delta\lambda$ vs $\lambda$ (Angstrom)

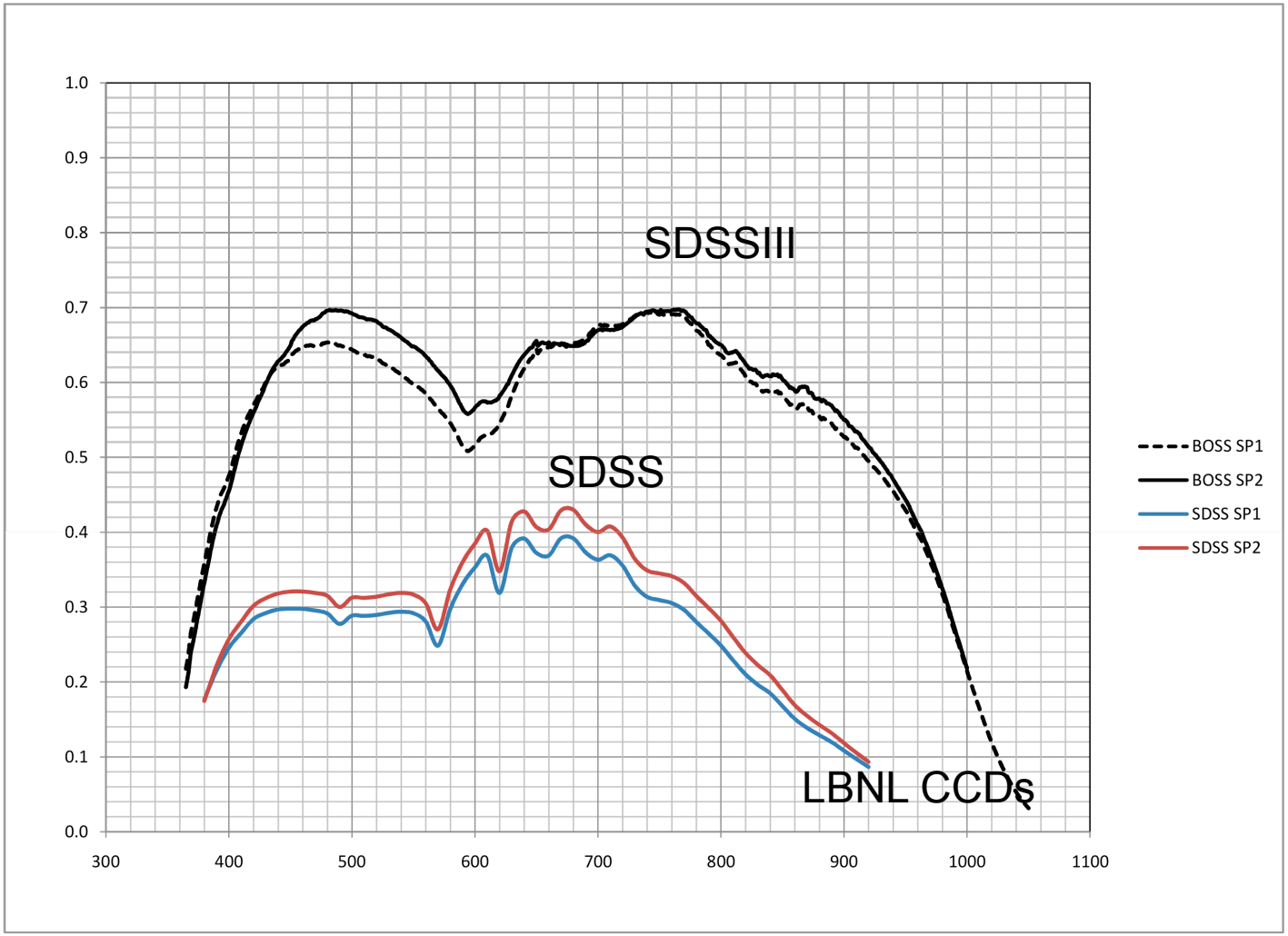



$\Delta v$ (km/s) vs redshift (LRGs)

<3% catastrophic failure



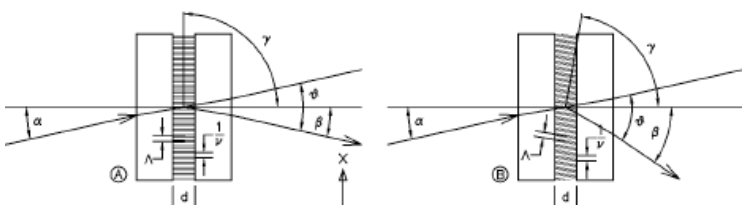
# Throughput Improvement

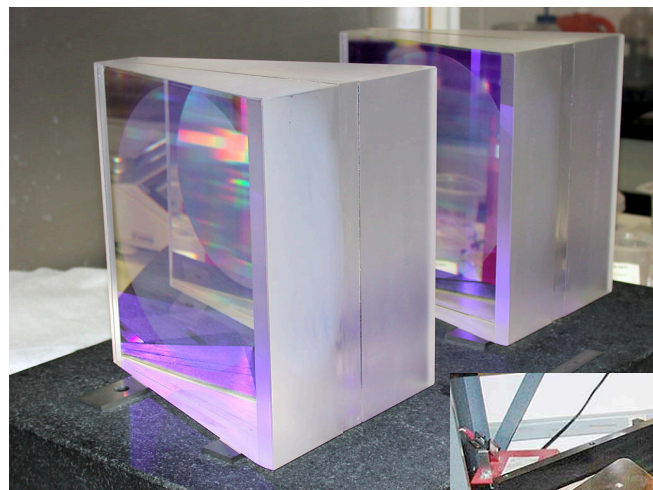



Starting from fiber output

# New Grisms

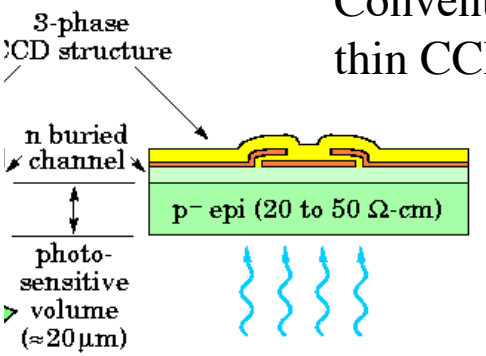
- Volume Phase Holographic dispersive element, sandwiched between two prisms
- Fabricated by Kaiser Optical Systems, Inc.
- Much better throughput than ruled gratings
- Slanted fringes to avoid “Littrow ghosts”



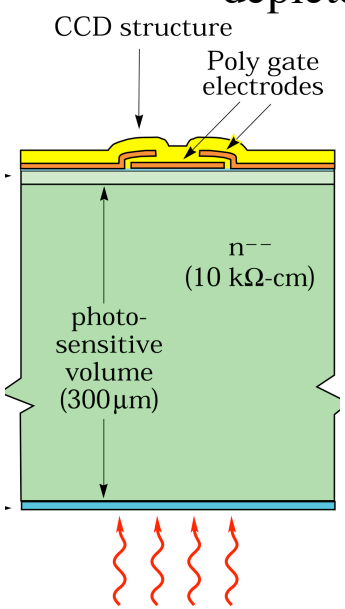


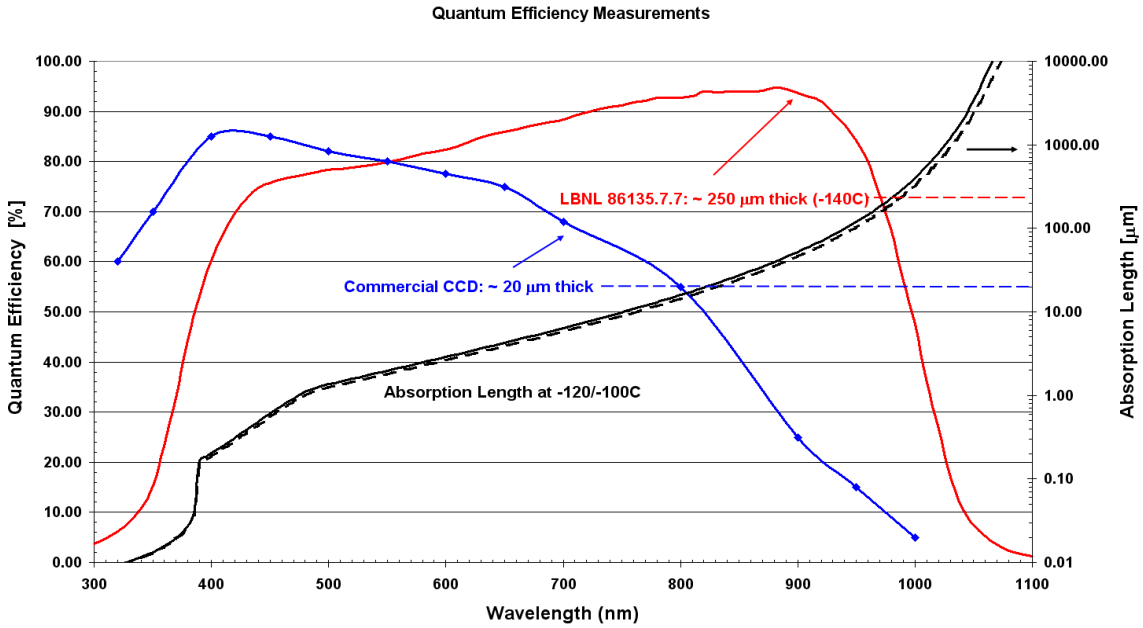
# LBNL 4k x 4k CCDs

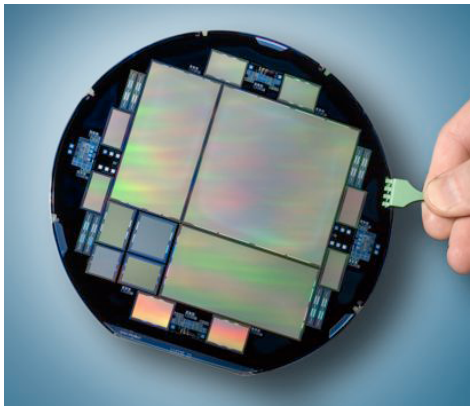
Conventional, thin CCD

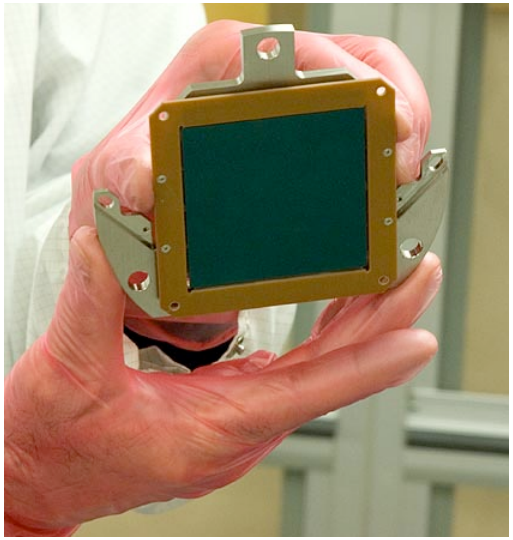



Thick, fully depleted CCD



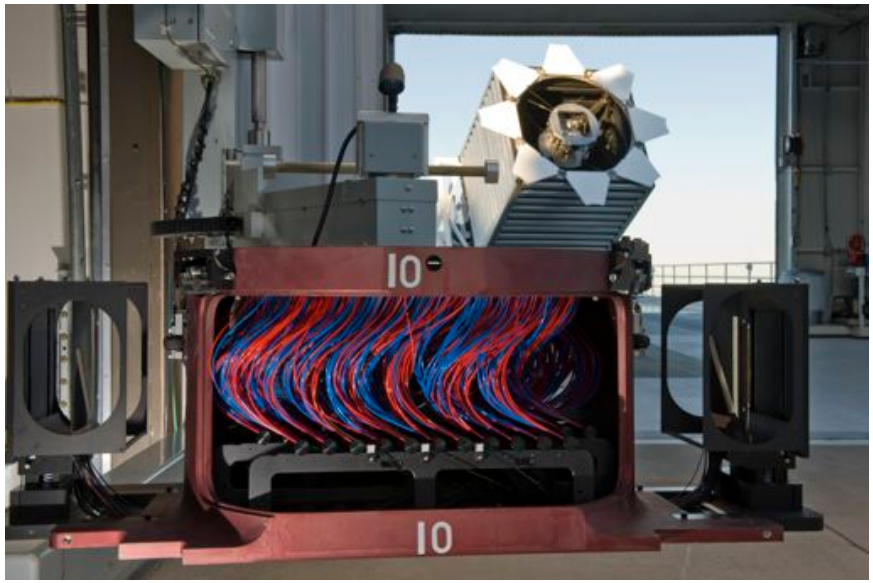





# Completed cameras

# BOSS Cartridges

- BOSS has 8 new cartridges with 1000, 120 μm thick fibers
  - Replace old cartridges with 640 fibers each, 180 μm thick
- First cartridge delivered in August 2009 – just in time for commissioning!
- Have completed 6 cartridges, remaining 2 in progress
- Plates are pre-drilled and plugged prior to each night's observations



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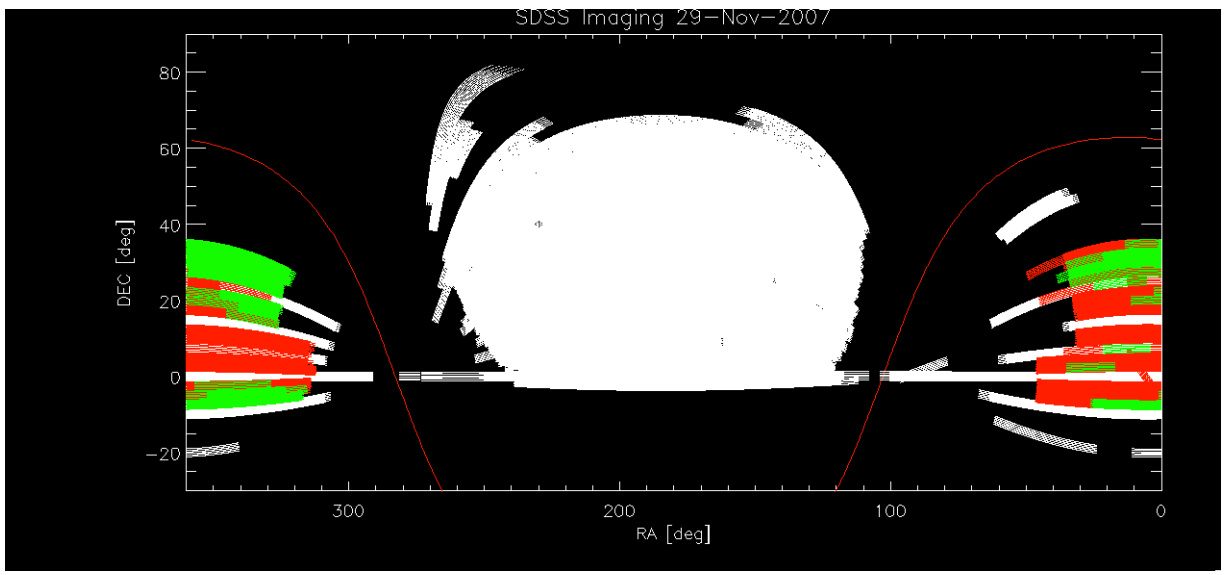
# BOSS Survey Plan

## ~2100 plates over 5 years

- 1.5M LRGs over 10,000 sq deg
  - 150 targets/sq deg
  - i<20, 0.3 < z < 0.8
  - galaxy target density of $3\times10^{-4}/(\mathrm{Mpc}/h)^3$ for 0.1< z < 0.6, dropping to 0 at z=0.8
- 150,000 QSO's over 8,000 sq deg
  - ~20 QSO's/sq deg from 40 targets
  - g<22, z > 2.2
  - Plus hi-z QSOs (z>3.5)



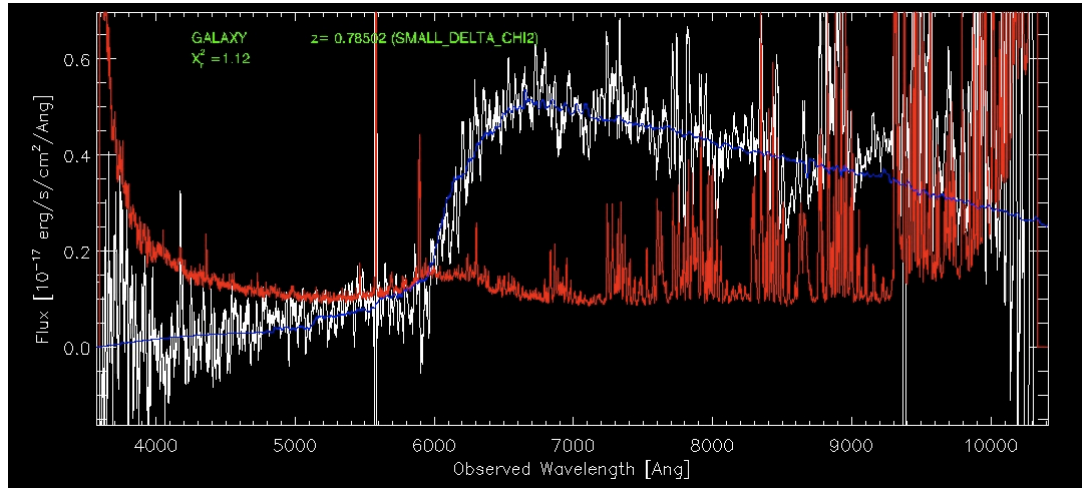

White: DR7 Imaging, ~8000 sq deg

Red/Green:
Additional BOSS imaging:

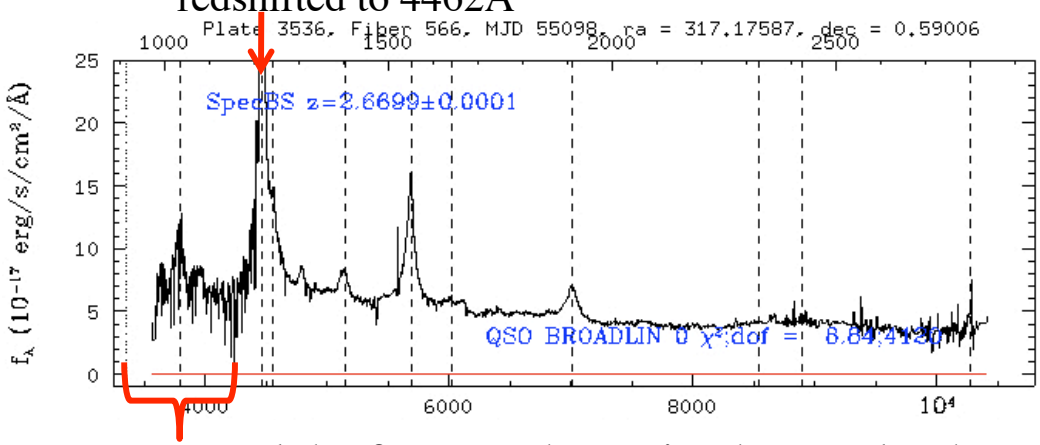
completed in 2008
Completed in 2009
Total ~3000 sq deg!

# BOSS First Light Sept 14, 2009! Commissioning Spectra

Luminous red galaxy at z=0.78 (galaxy in white, sky bkgd in red)




H-alpha emission at 1216A, redshifted to 4462A

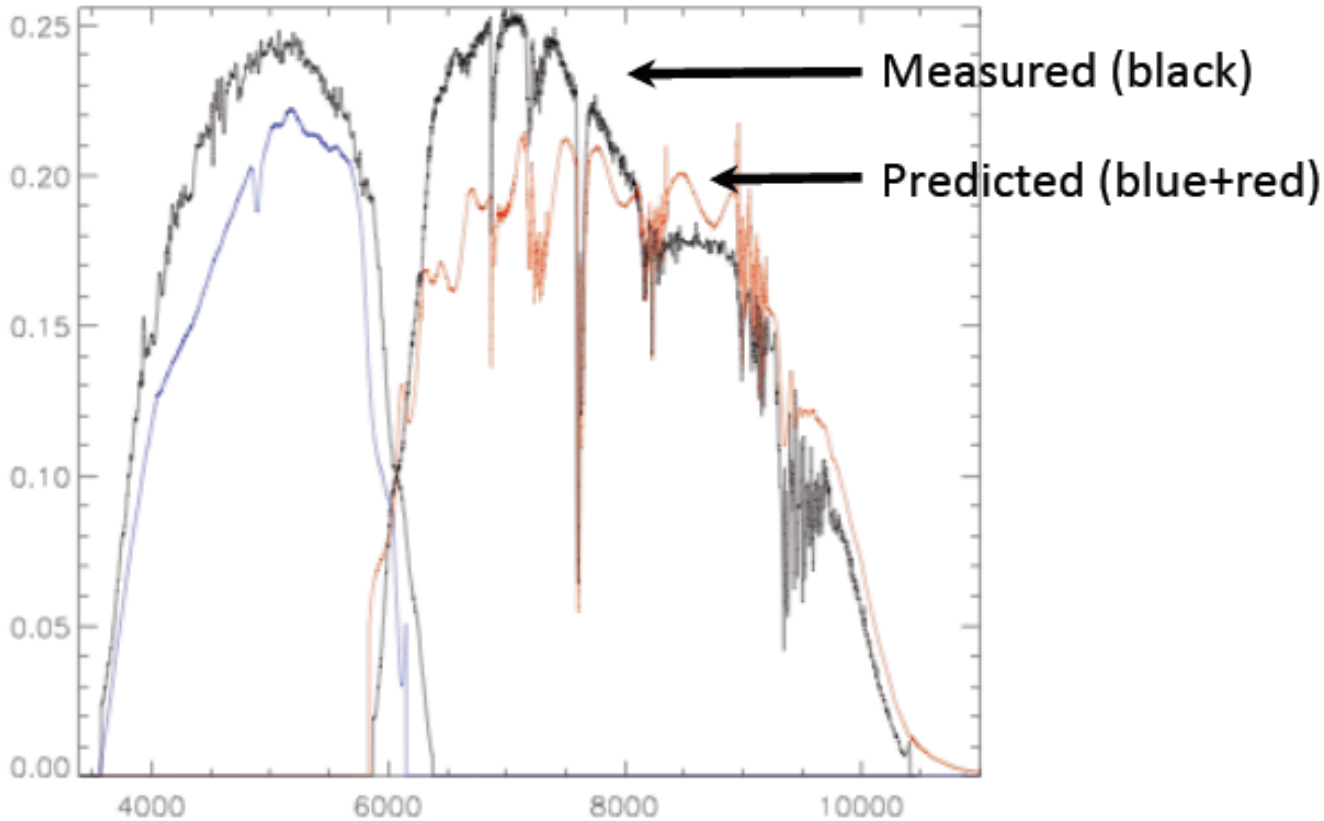



Quasar at z = 2.67

Lyman-alpha forest – absorption by $H_2$ clouds tracing the distribution of large scale structure in the universe

# Preliminary BOSS throughput

Uncertain due to seeing+gain factors (over-estimated?)

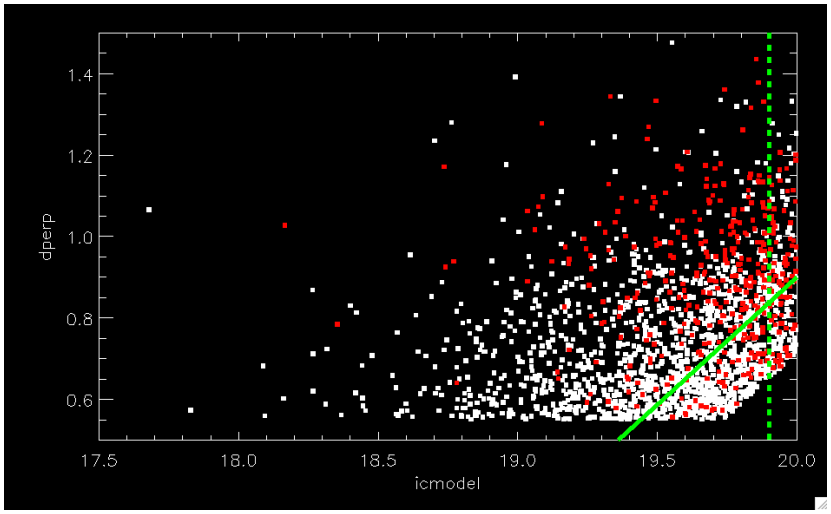



Includes atmosphere

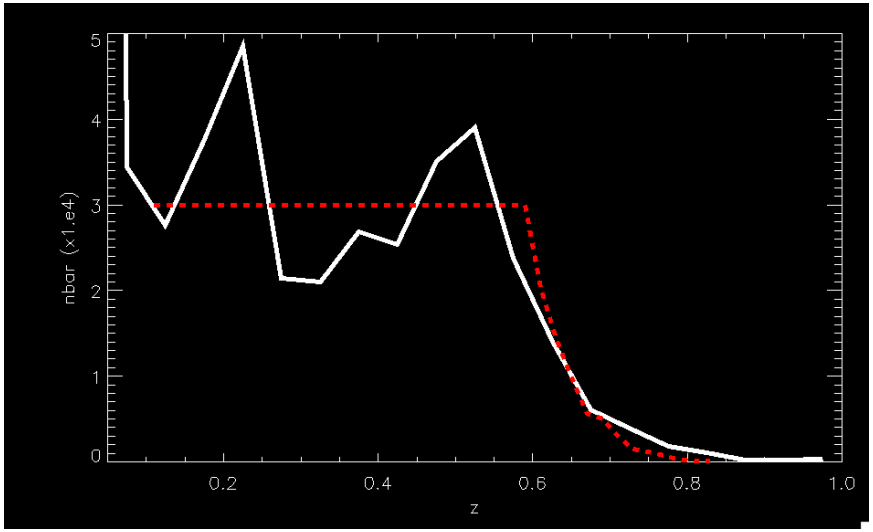
# BOSS Target Selection

- Commissioning plates with higher target density used to test target selection algorithms
- LRGs
  - Results are as expected; ~95% efficiency
- QSOs
  - A hard problem due to overlap with stellar locus
  - Combine 3 different algorithms
  - Currently achieving ~15/sq deg out of 40 targets
    - Will continue to tweak and add additional data, eg GALEX UV data, Palomar Transient Factory for variability info

# LRG Target Selection




- Proposed target selection cuts (compared with the commissioning data). The red points are z>0.6 galaxies.




- Best guess at the co-moving number density that these cuts yield. The dashed line is what we assumed for all our forecasts.

N. Padmanabhan

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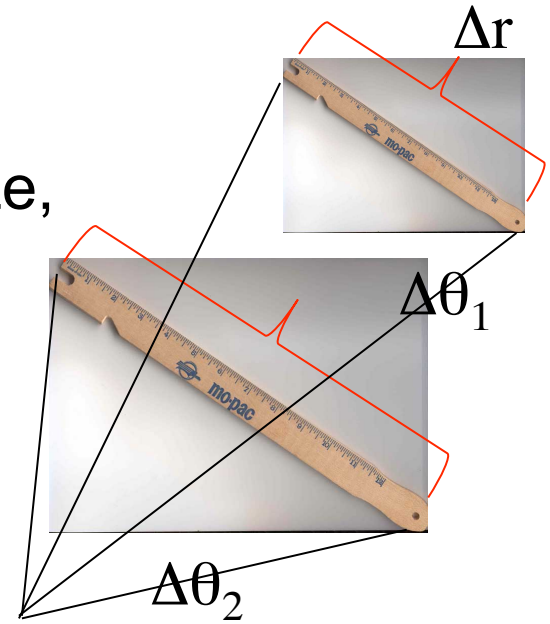
    - Quasars
    - Redshift space distortions
    - Galaxy-galaxy lensing
  - Galaxy evolution
  - Quasar demographics
- Conclusions and Outlook

# Standard Candles and Standard Rulers

- Want to measure scale factor a(t) vs. time
- Redshift gives scale factor a = 1/(1+z)
- Distance gives "look back time", t = D/c
- Standard candles have known intrinsic luminosity, so observed brightness is a proxy for distance
  - eg, Type Ia SNe => first detection of accelerating expansion in 1998
- Standard rulers have known (co-moving) size, so observed size is a proxy for distance:

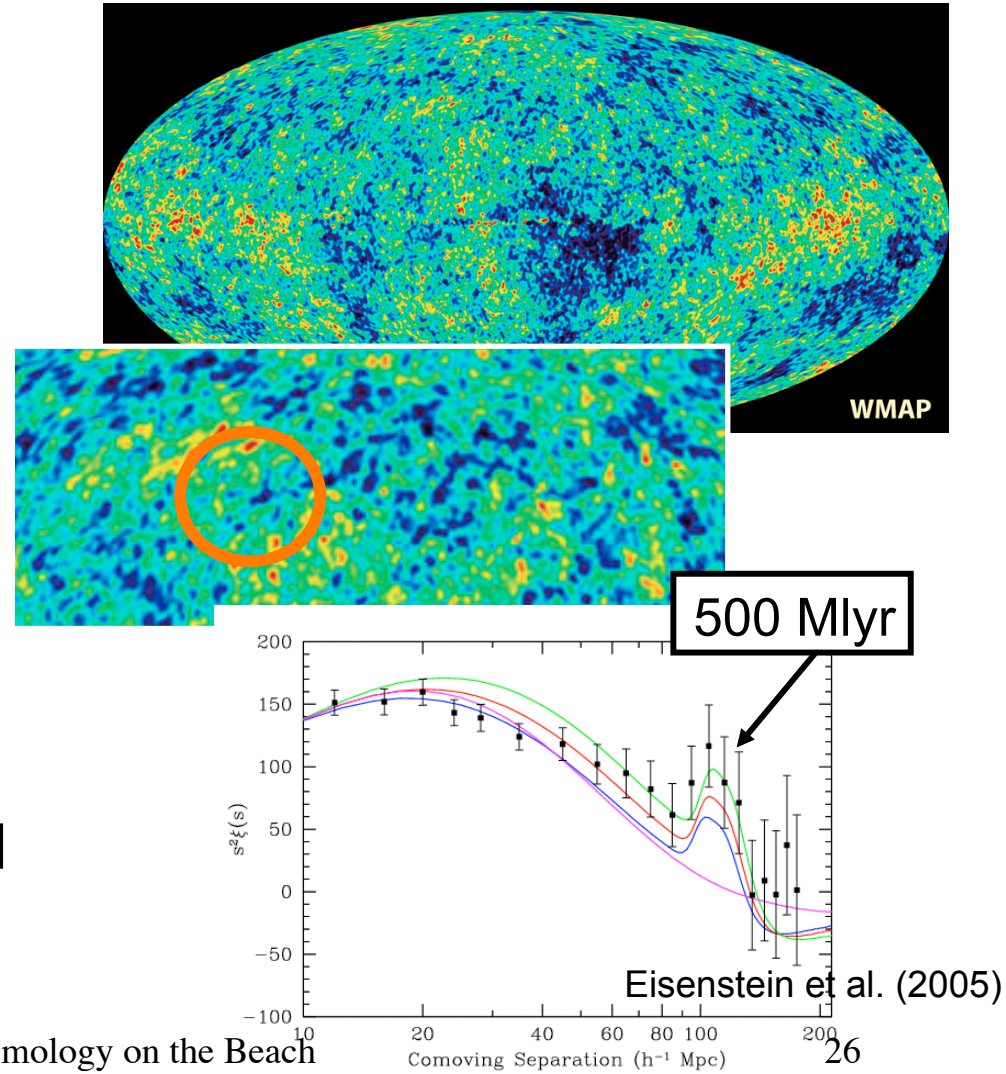



Angular diameter distance: $d_A = \Delta r/\Delta\theta$

Along the line of sight: $H(z) = c\,\Delta z/\Delta r$

# Baryon Acoustic Oscillations: A New Method for Robust Distances

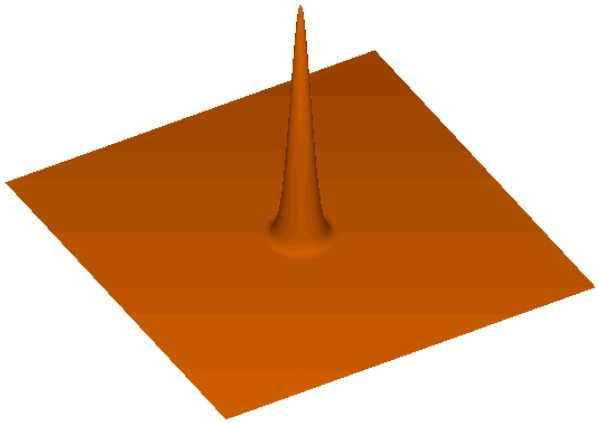
- Sound waves in the first million years of the Universe create a preferred length scale.
  - Seen as Doppler peaks in the cosmic microwave background.
- These peaks are also visible in structure of galaxies.
  - Galaxies are more likely to be separated by 150 Mpc
- First convincingly detected in SDSS in 2005: 4% distance measure.




Eisenstein et al. (2005)

# More on the Acoustic Sound Wave

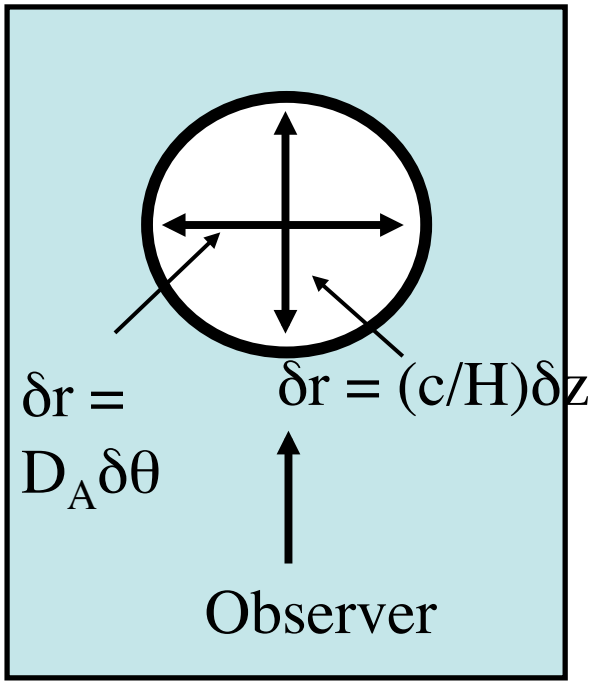
- In hot ionized early Universe, photons are tightly coupled to e- and p in the plasma
- Each initial over-density (in DM & gas) creates an overpressure in photons that launches a spherical sound wave
- This wave travels outwards at 0.57 c
- As Universe cools, H atoms form and photons decouple. CMB travels to us from this “surface of last scattering”
- Sound wave stalls at a radius given by 400,00 yrs x 0.57c ~150 Mpc
- Over-density in shell (gas) and in the original center (DM) seed the formation of galaxies.



***Preferred separation of 153.5 Mpc (WMAP 5$^{th}$ year data)***

# Advantages of BAO

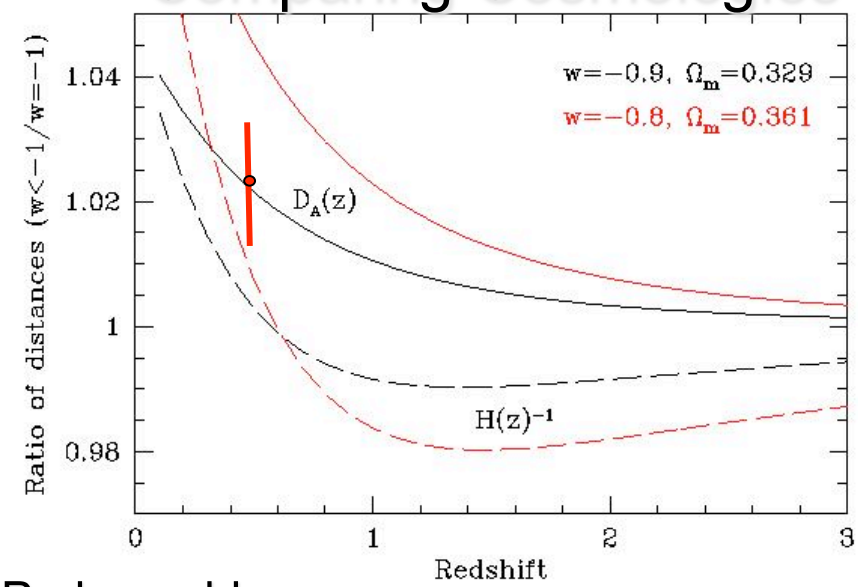
- The acoustic oscillation scale is fixed at z~1100 by CMB
  - Well measured by WMAP, Planck
- BAO provides a standard ruler, both along and across the line of sight
  - Intrinsic cross check ($D_A$ is an integral of H)
- Robust, large scale – 150 Mpc
  - Non-linear effects mild
  - Modest requirements on redshift accuracy
- ***But need large survey volume!***
  - ***And many objects to sample the density field well enough to get above shot noise***



# BOSS Goal is 1% Distance Measurement

- Dark energy is parameterized by the equation of state, $w = p/\rho$; want to distinguish from cosmological constant, w=-1, and study w(z).

Comparing Cosmologies

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- Varying *w* assuming perfect CMB:
  - Fixed $\Omega_m h^2$
  - $D_A(z=1000)$
- *w*(*z*) is even harder.
- Need 1% distance measurements!

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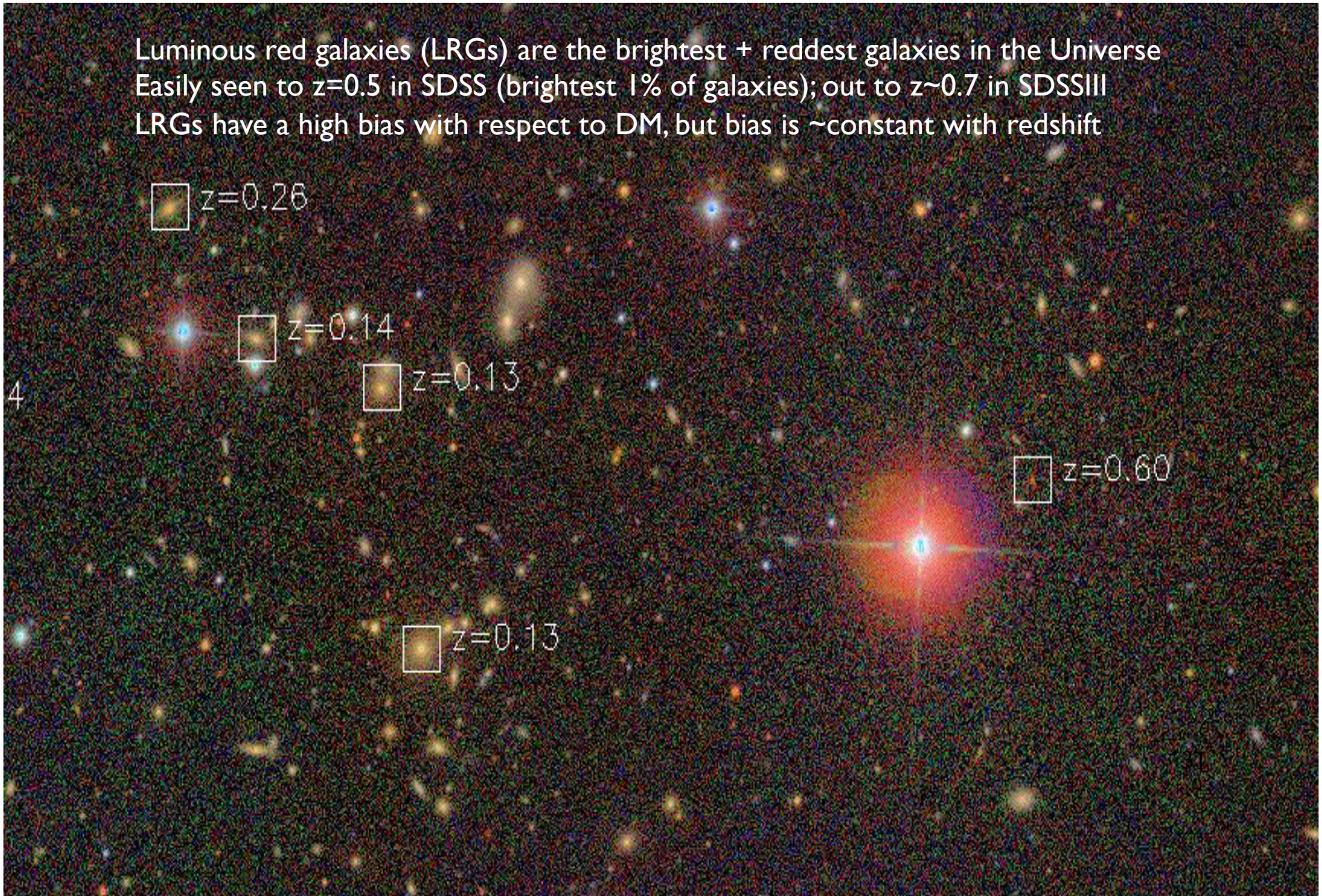
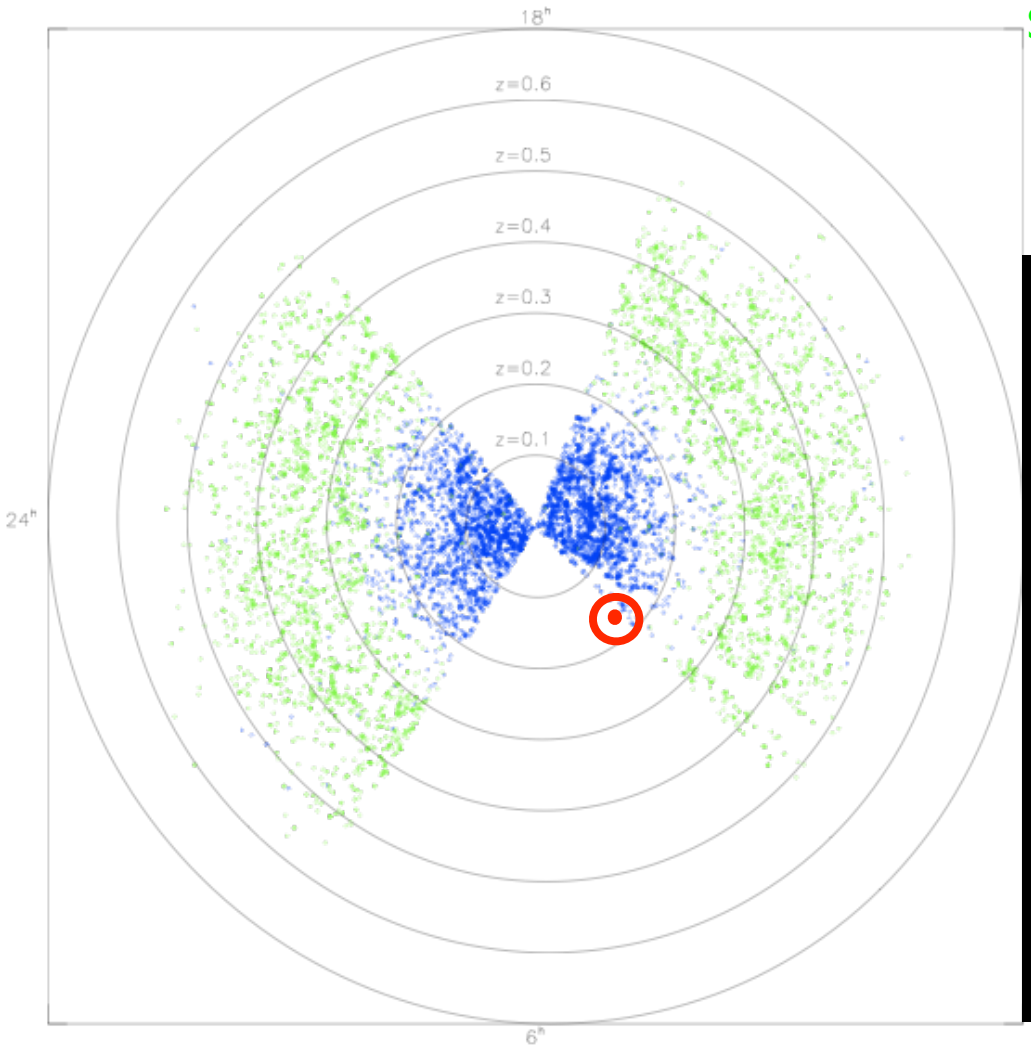
# LRGs: Tracers of high z structure

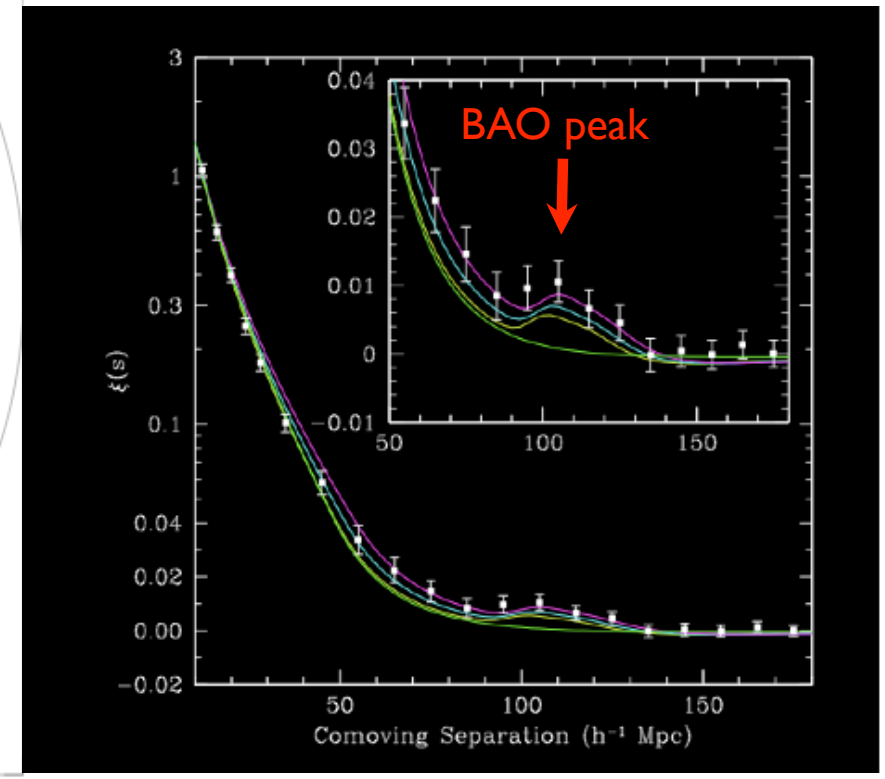


# SDSS Spectroscopic Luminous Red Galaxies

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 over 3700 $deg^2$ 2004

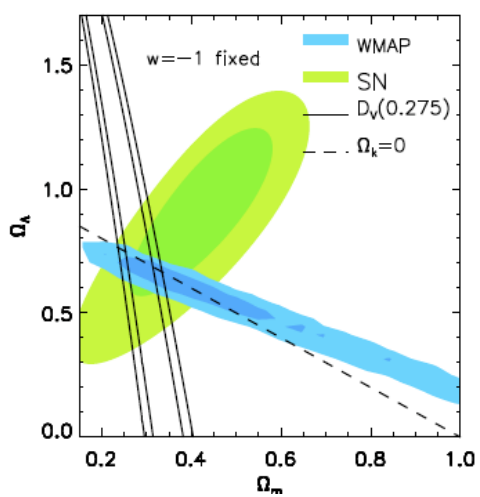


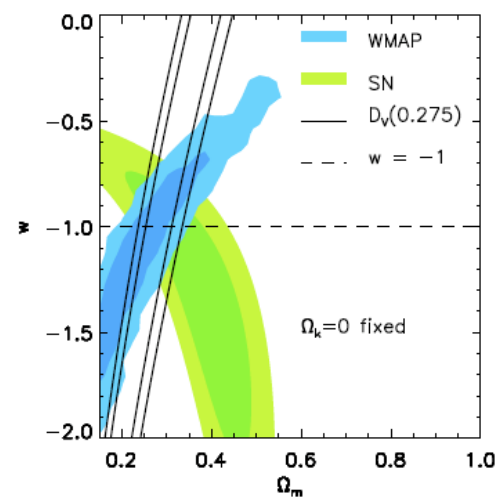



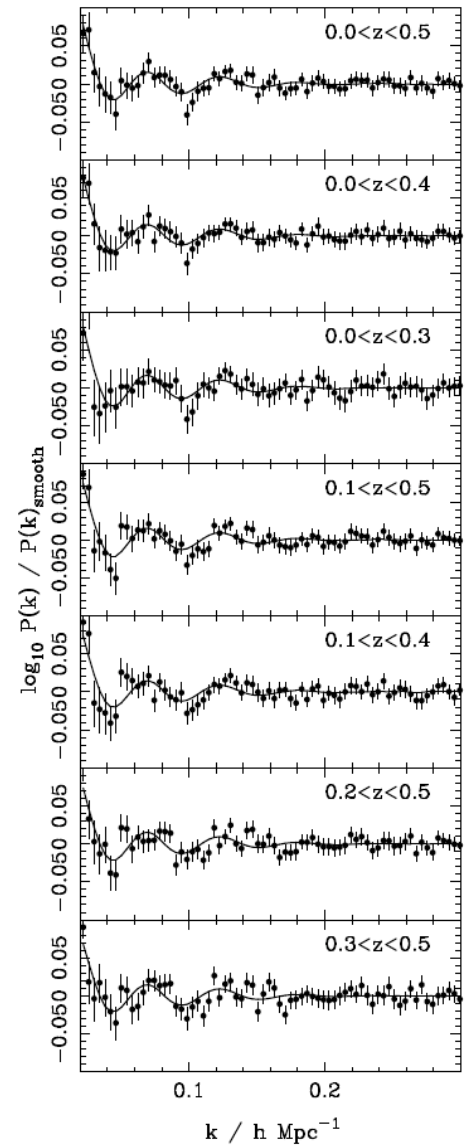

Eisenstein et al 2005
4% distance measurement

# Current State of the Art

- Results from final SDSS DR7 are available (~100K LRGs)
  - Percival et al 2009: 2.7% distance measurement; power spectrum analysis
  - Reid et al 2009: extract underlying DM halo density field => add'l constraints, eg $\Sigma m_\nu$
  - Kazin et al 2009: correlation function analysis; see talk tomorrow



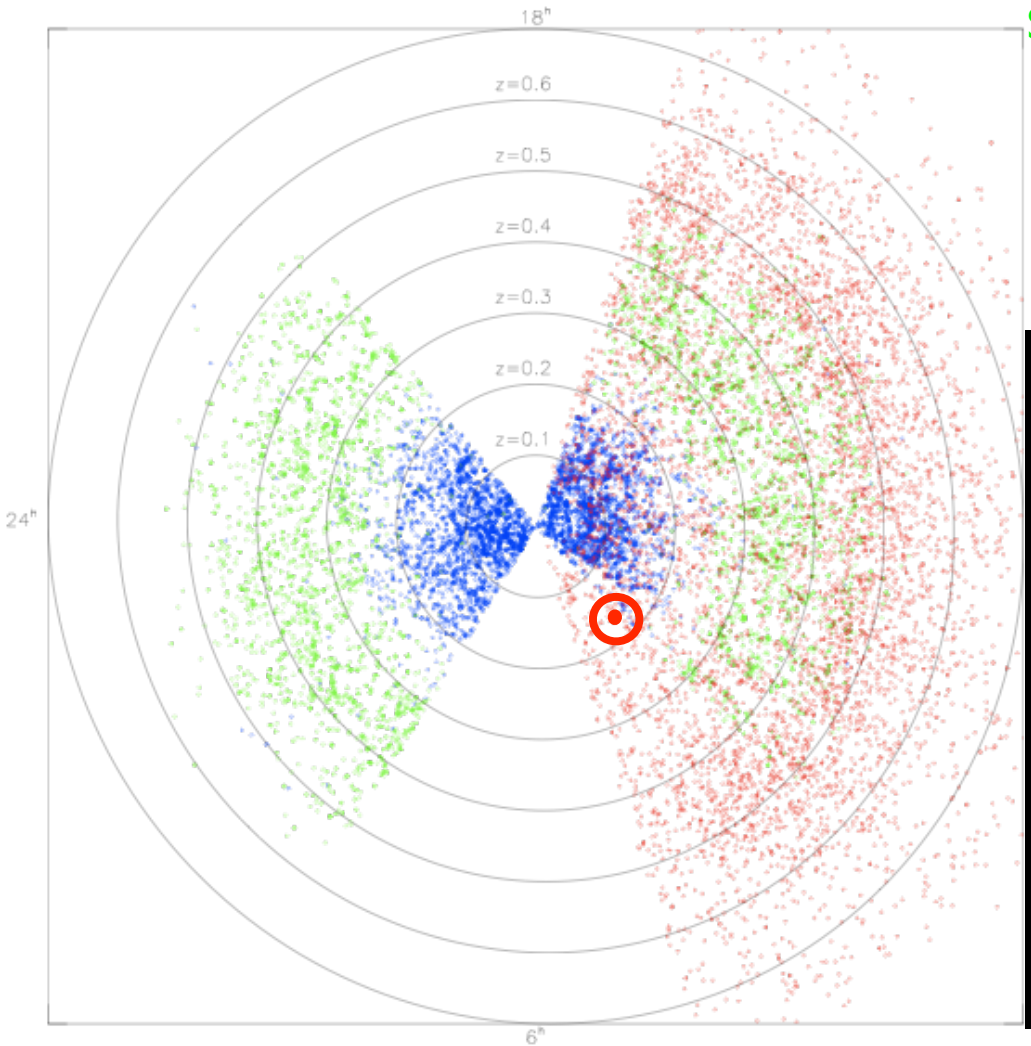



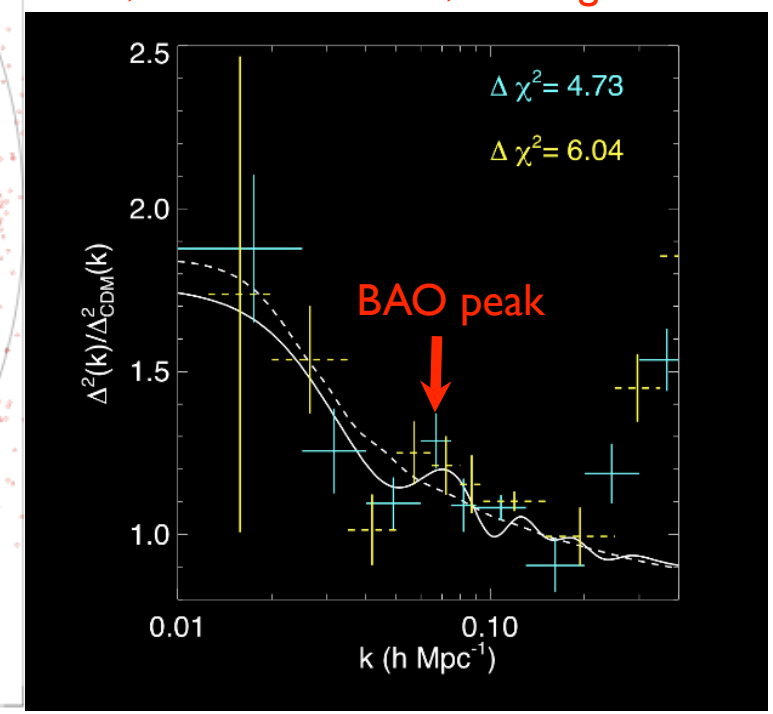
# SDSS Photometric Luminous Red Galaxies

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 over 3700 deg$^2$ 2004
100,000 galaxies over 8500 deg$^2$ by 2008

SDSS photo-z
600,000 LRGs over 3,500 deg$^2$




Padmanabhan et al 2007

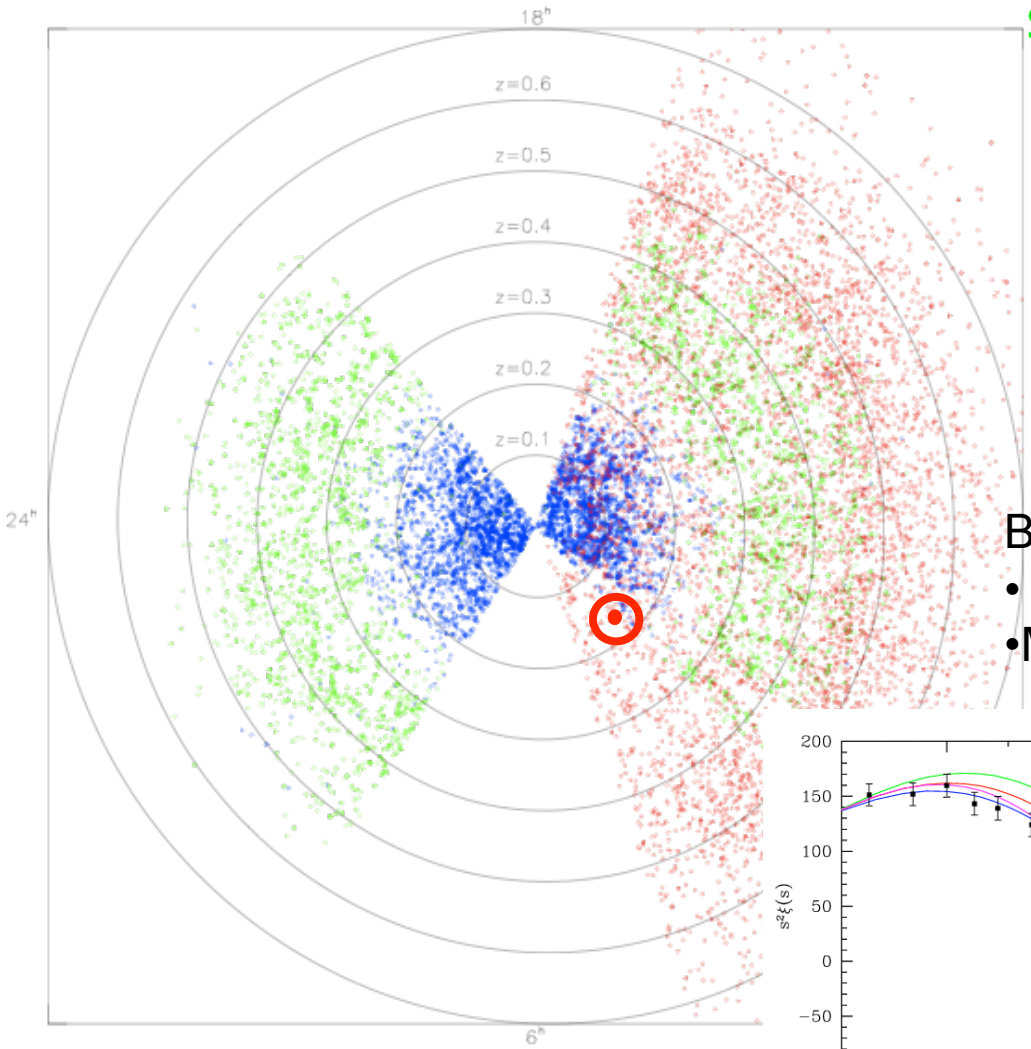
6% distance measurement

# BOSS: Turn SDSS photo-z sample → spectro-z

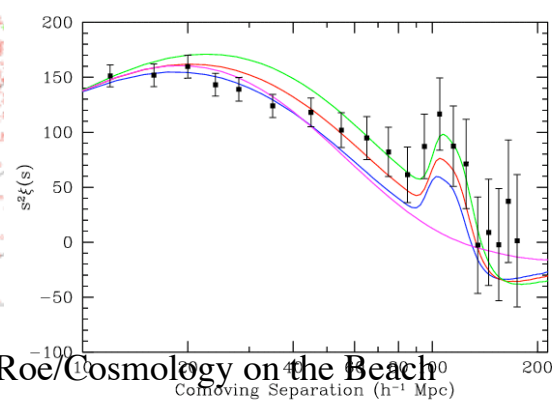
SDSS main galaxy survey
- ~1 million galaxies
- Too little volume for BAO

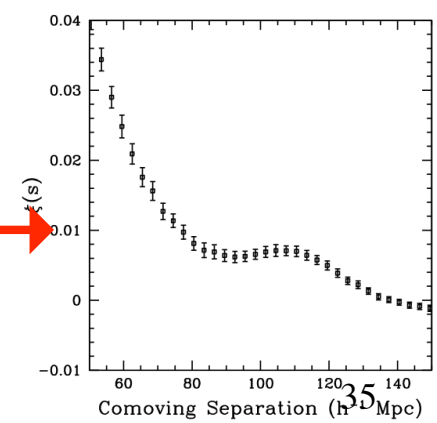
SDSS luminous red galaxies (LRGs)
- Sparse sampled at $10^{-4}$ galaxies/Mpc$^3$
- 47,000 galaxies by 2004
- 80,000 galaxies by 2008
- 8000 deg$^2$ (finish in 2008)

BOSS red galaxies
- 1.5M galaxies over 10,000 deg$^2$
- $0.1 < z < 0.7$
- 7x volume of SDSS and 2x better sampling



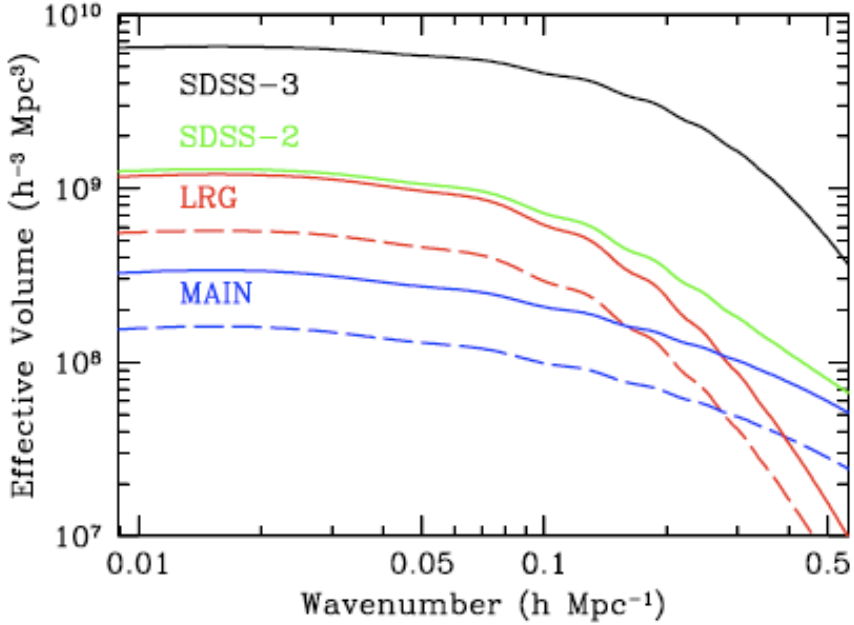

BOSS LRG Science Goals:
- Measure $D_A$ at z=0.3 and 0.6 to ~1%
- Measure H at z=0.3 and 0.6 to 2%



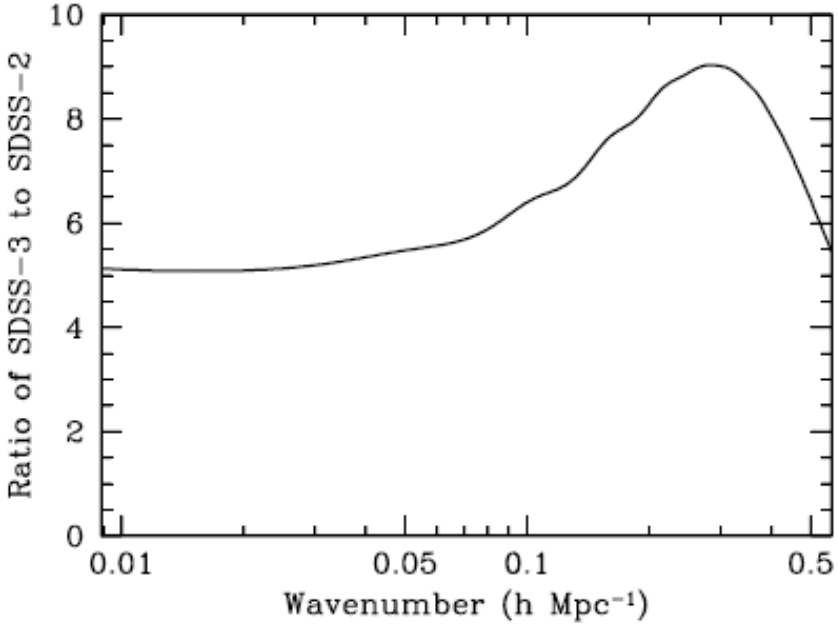



# SDSS-III LRG Sample

Volume vs Wave Number, SDSS II vs IIII




Ratio of SDSS III to II vs Wave Number

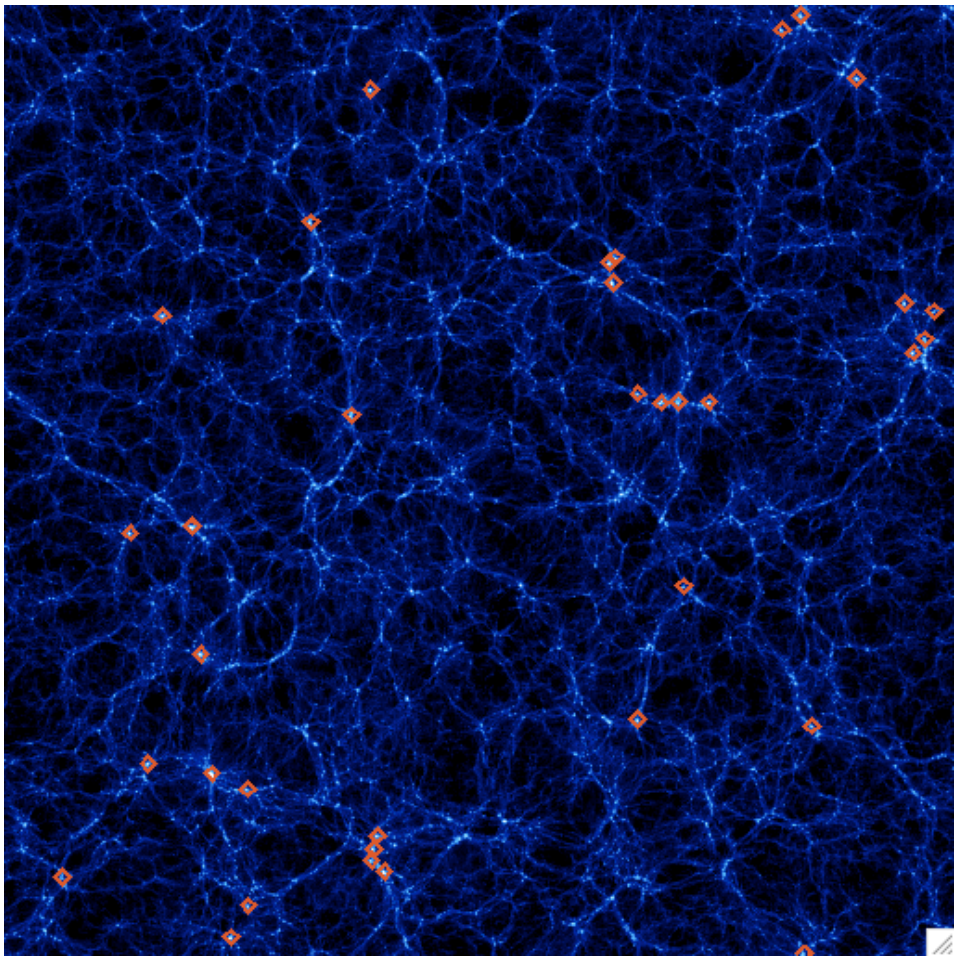


# Figure of merit nP

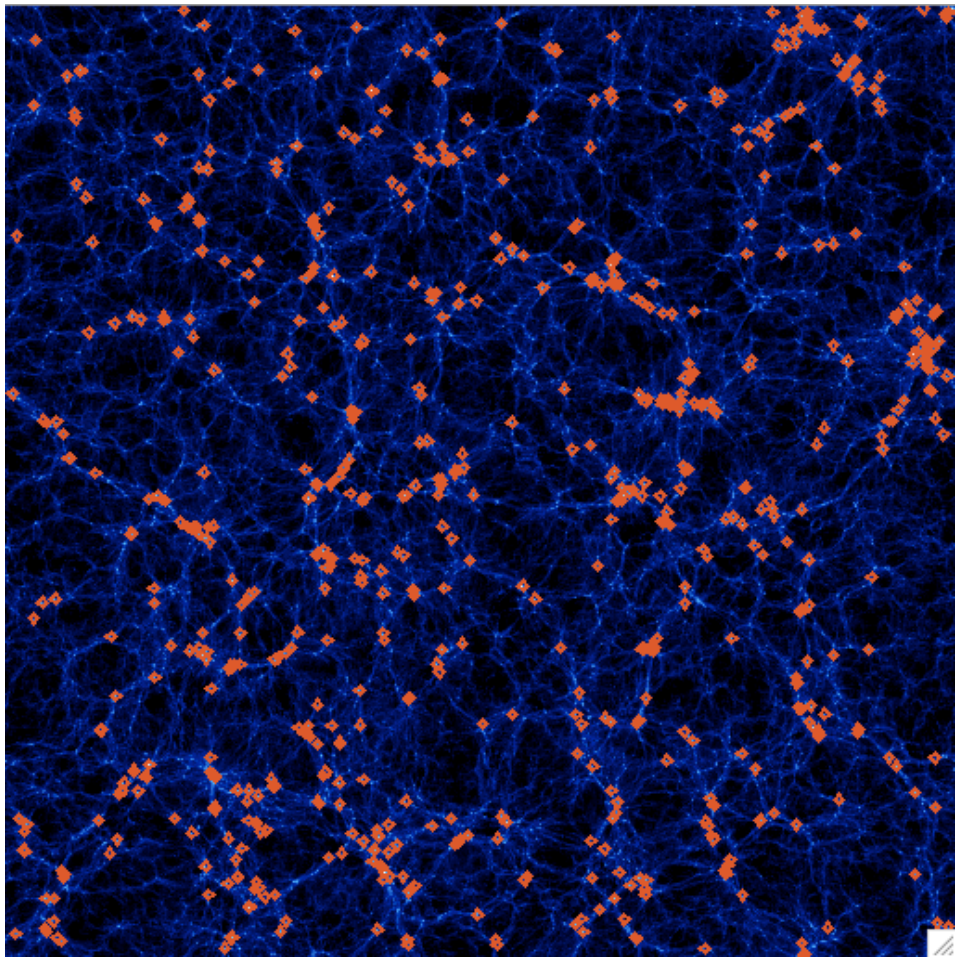
- n= number density, P=power spectrum at wave number of interest
- For SDSS, nP~0.5 at k=0.2 h/Mpc
  - Dominated by shot noise
- For BOSS, aim for nP~2 to reduce shot noise
  - $n=3 \times 10^{-4}$ $(h/Mpc)^3$ for P~7000 $(Mpc/h)^3$
  - Improvement over SDSS I similar to that of Planck over WMAP! X7 more modes due to increase in volume and better sampling

# Sampling the cosmic density field

SDSS-I and SDSS-II



BOSS

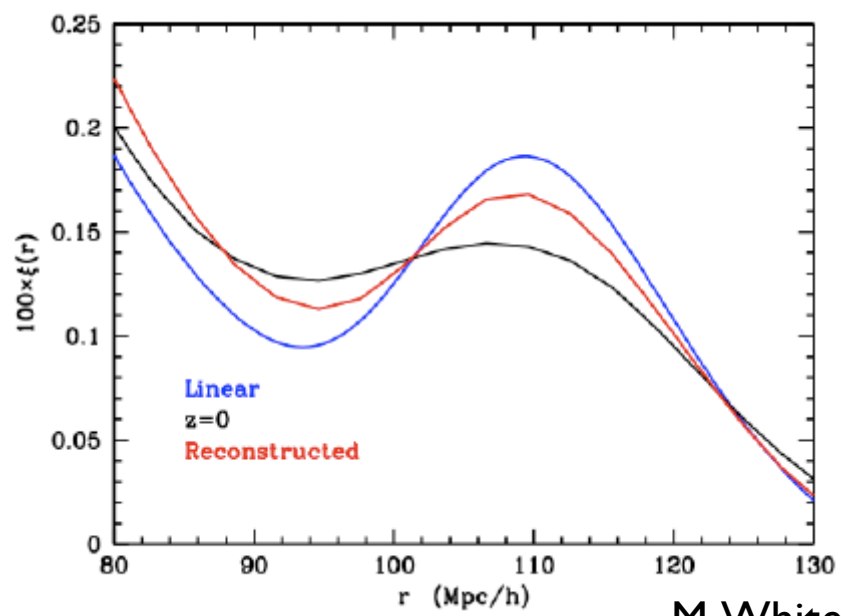


A slice 500 $h^{-1}$Mpc across and 10 $h^{-}$ Mpc thick at z=0.5

M. White

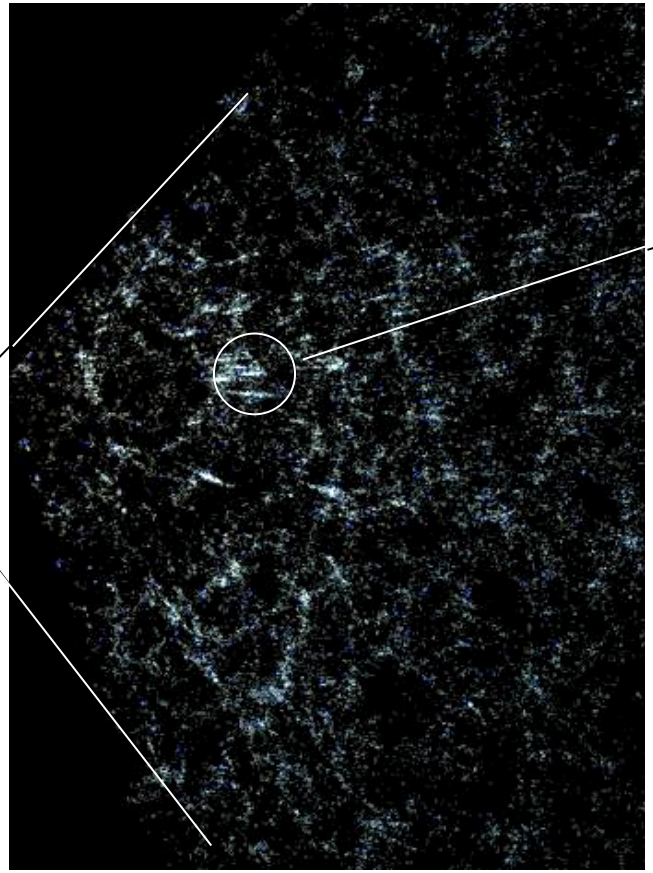
# Non-linear Effects

- The BAO peak is smeared out in later times by the non-linear effects of gravity tugging on galaxies
  - Peak is both broadened (10%) and shifted (0.5%)
  - Shift must be corrected for 1% precision
- Better sampling of density field allows reconstruction of large scale density flows, to restore linear theory
- BOSS projections assume 50% reconstruction
- Seems doable based simulations, but has not yet been demonstrated on data




M. White

# Example of Non-Linear Effects



"Fingers of God" are due to peculiar velocities of galaxies in a cluster due to gravitational effects.

Improved treatment in Reid et al 2009 for broad band power spectrum; will be necessary to do even better for BOSS

# Outline

- BOSS Overview
  - SDSS-III
  - Spectrograph upgrade
  - Survey status
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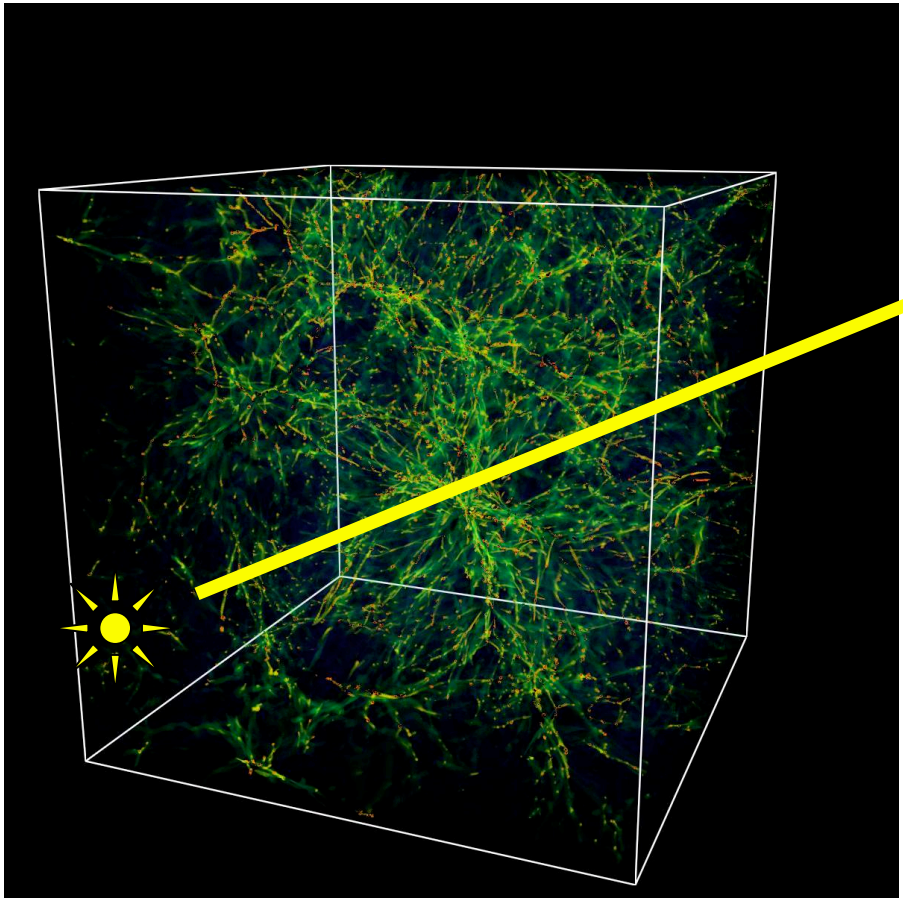
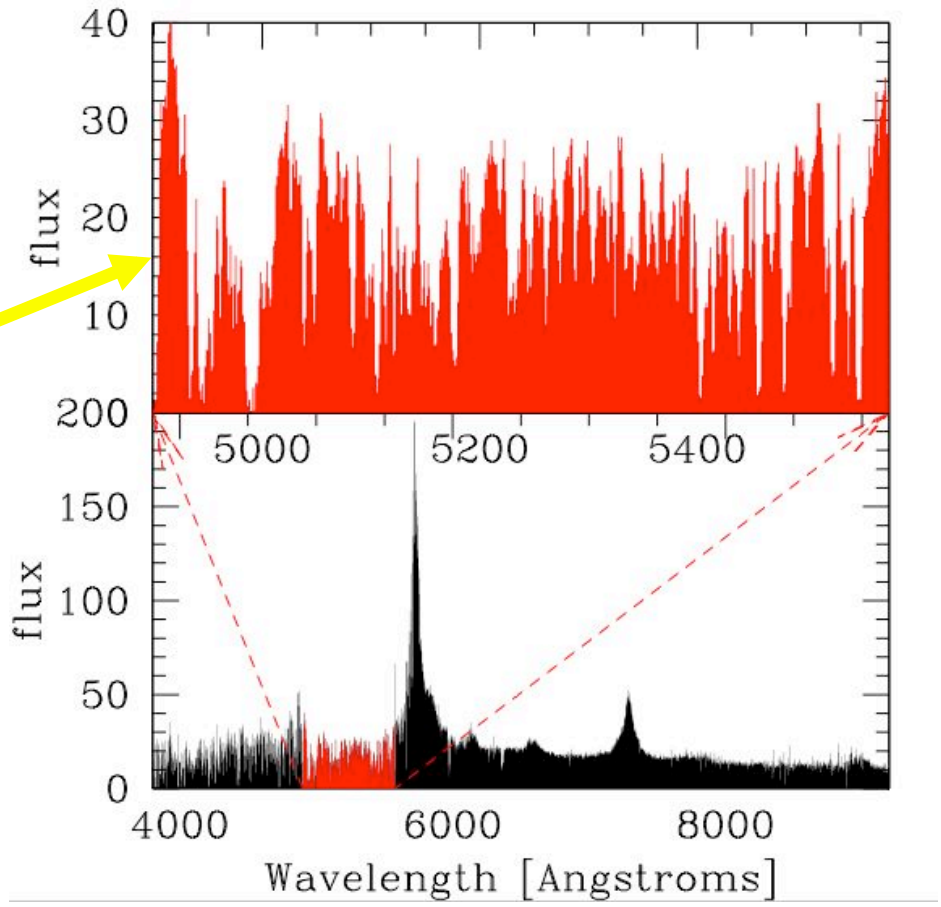
  - Baryon Acoustic Oscillations
    - LRGs
    - Quasars
  - Ancillary Science
- Conclusions and Outlook

# On to higher redshift: Lyman alpha forest

Neutral H simulation
(25 $h^{-1}$Mpc box, R. Cen)

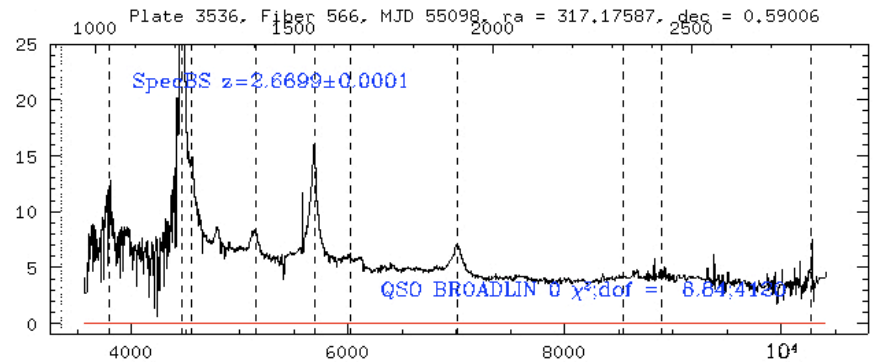


Neutral H absorption observed
in quasar spectrum at z=3.7



# BOSS Quasar Survey

- A dense grid of distant quasars will show the acoustic signature in the large-scale clustering of neutral H




- BOSS will observe 150,000 quasars over 8,000 sq deg
  - ~20% piggyback program on BOSS galaxies
  - BAO technique measures $D_A$ to 1.5% and H to 1.2% at $z = 2.5$.
  - Powerful constraint on spatial curvature and high-redshift dark energy; look for signature of "early dark energy"
- BOSS is a pathfinder for this technique; many challenges, beginning with target selection!

# BOSS: sampling the cosmic density field w/ QSO "skewers"

SDSS-I and SDSS-II

BOSS

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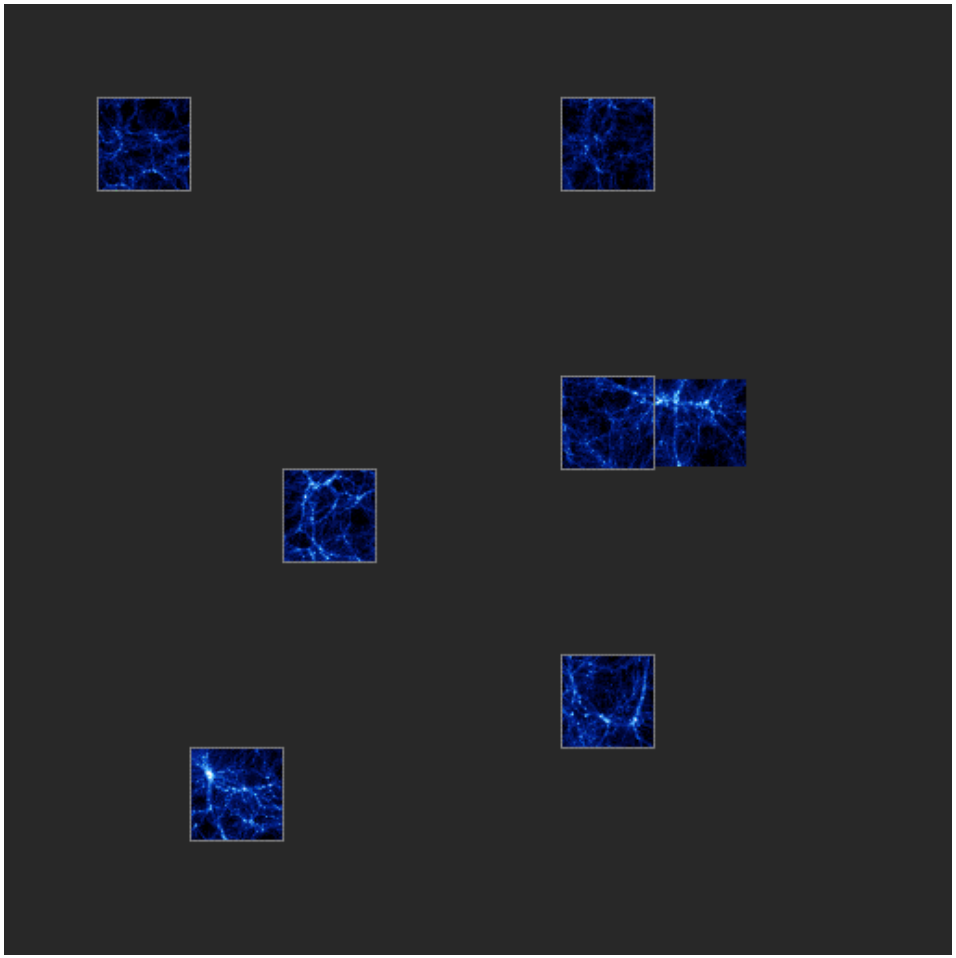

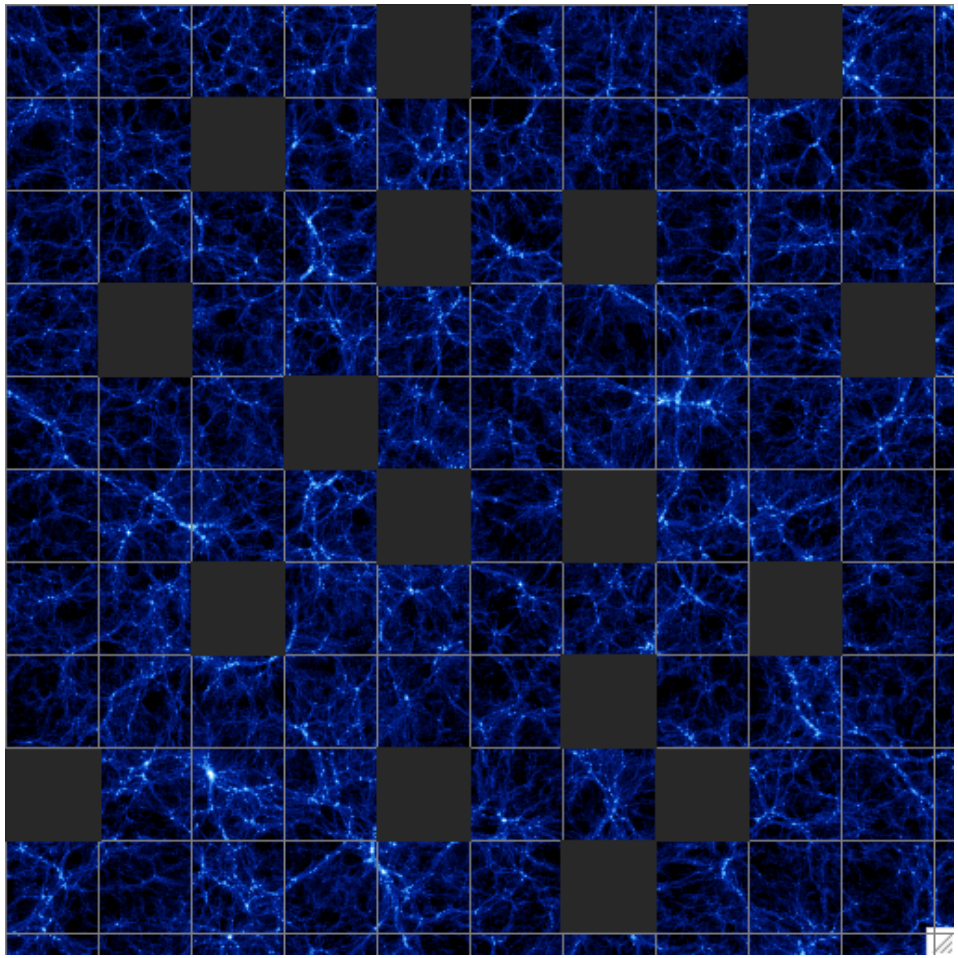

Horizon simulation: 500 $h^{-1}$Mpc box

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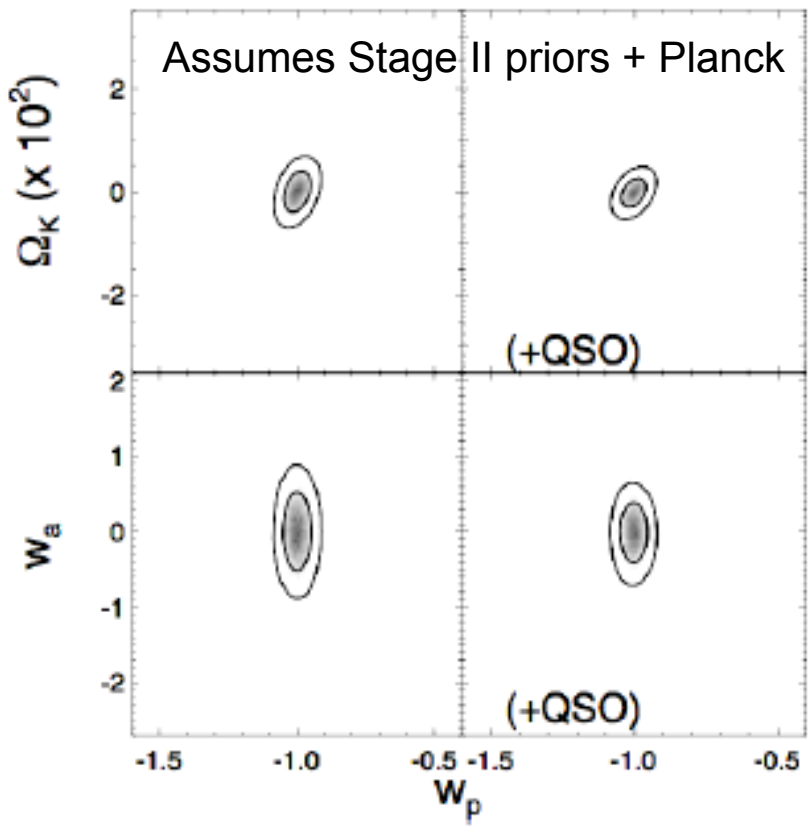
# BOSS Cosmology Constraints with LRGs and LRG + QSOs

- 3% on $w_p$, 30% on $w_a$, 0.2% on $\Omega_k$
- These constraints improve by a further factor of ~2 if we can model the BOSS broad band power



# BOSS Forecasts

| | $h$ | $\Omega_K$ | $w_0$ | $w_p$ | $w_a$ | FoM |
|---|---|---|---|---|---|---|
| **Min. Requirement Projections:** | | | | | | |
| **BOSS Gal** | **0.009** | **0.0028** | **0.089** | **0.032** | **0.370** | **83** |
| **BOSS Gal+QSO** | **0.009** | **0.0022** | **0.080** | **0.031** | **0.302** | **107** |
| Forecast Projections: | | | | | | |
| BOSS Gal | 0.008 | 0.0028 | 0.089 | 0.032 | 0.366 | 86 |
| BOSS Gal+QSO | 0.008 | 0.0019 | 0.076 | 0.029 | 0.279 | 122 |
| +WL | 0.008 | 0.0017 | 0.068 | 0.026 | 0.227 | 172 |
| +CL | 0.008 | 0.0018 | 0.071 | 0.023 | 0.244 | 177 |
| +SN | 0.006 | 0.0019 | 0.052 | 0.023 | 0.220 | 199 |
| +WL+CL+SN | 0.005 | 0.0016 | 0.046 | 0.018 | 0.164 | 331 |
| Forecast Projections w/Broad-Band Power: | | | | | | |
| BOSS Gal+QSO | 0.007 | 0.0015 | 0.065 | 0.016 | 0.240 | 257 |
| +WL+CL+SN | 0.005 | 0.0013 | 0.041 | 0.014 | 0.150 | 479 |

Stage II priors + Planck

+ Stage III

Full power spectrum

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# Ancillary Science

- BOSS will enable many other results
  - Other science with LRG and QSO data
    - Structure formation
    - Galaxy formation & evolution
    - Galaxy – galaxy lensing (spectro z for lens)
    - QSO demographics, QSO clustering, x2 QSOs at z > 3.5
  - Piggyback program: ~10 fibers per field
    - ~dozen proposals selected

# Conclusions

- BOSS will be the definitive large scale structure survey for z<0.6
- BOSS will make first measurement of DE at z>2
- BOSS Science Goals
  - LRGS: 1% $d_A$, 2% H(z) at z = 0.35, 0.6
  - QSO's: 1.5% $d_A$, H at z ~ 2.5
  - More constraints through full power spectrum
  - Ancillary science
- BOSS is off to a good start – look for first results in the coming year!