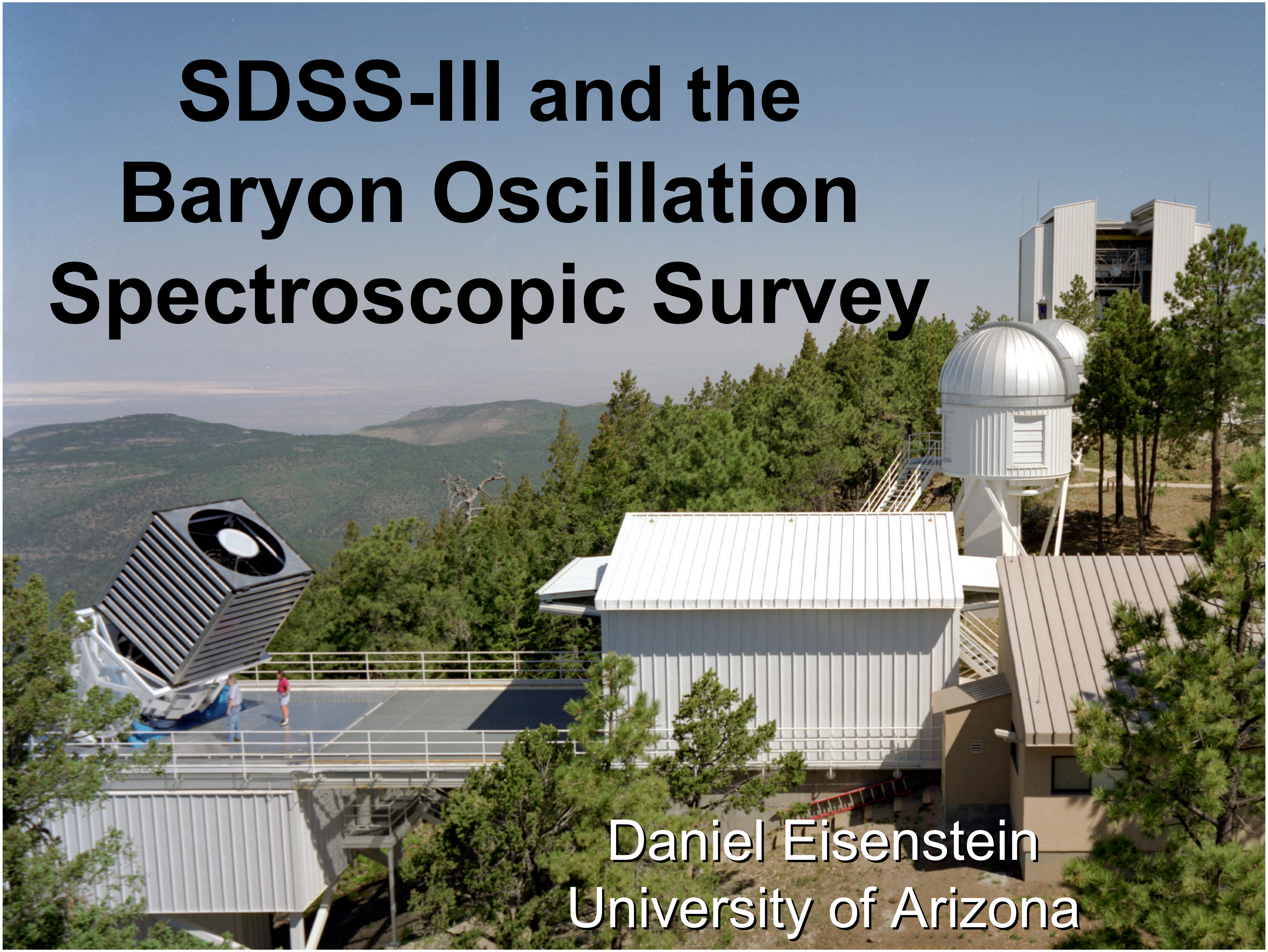
SDSS-III and the Baryon Oscillation Spectroscopic Survey

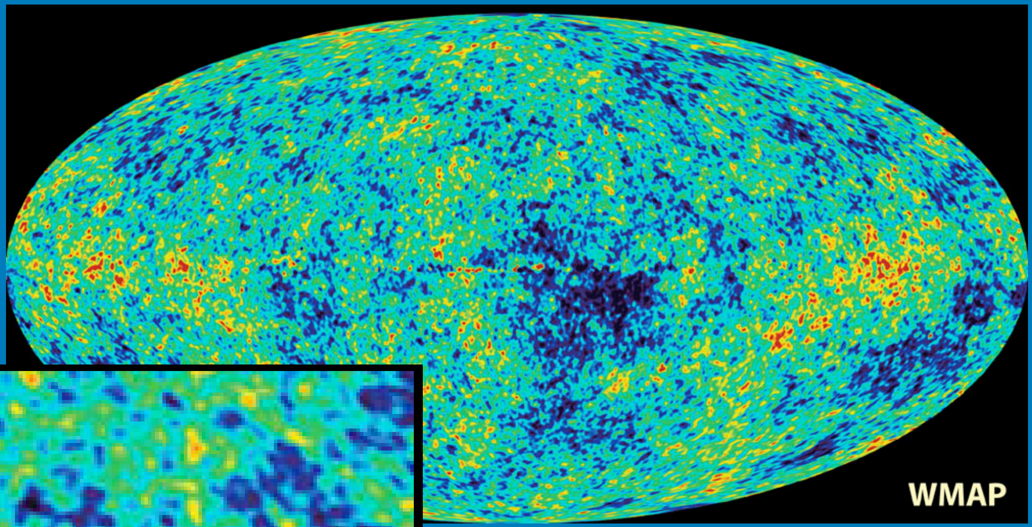


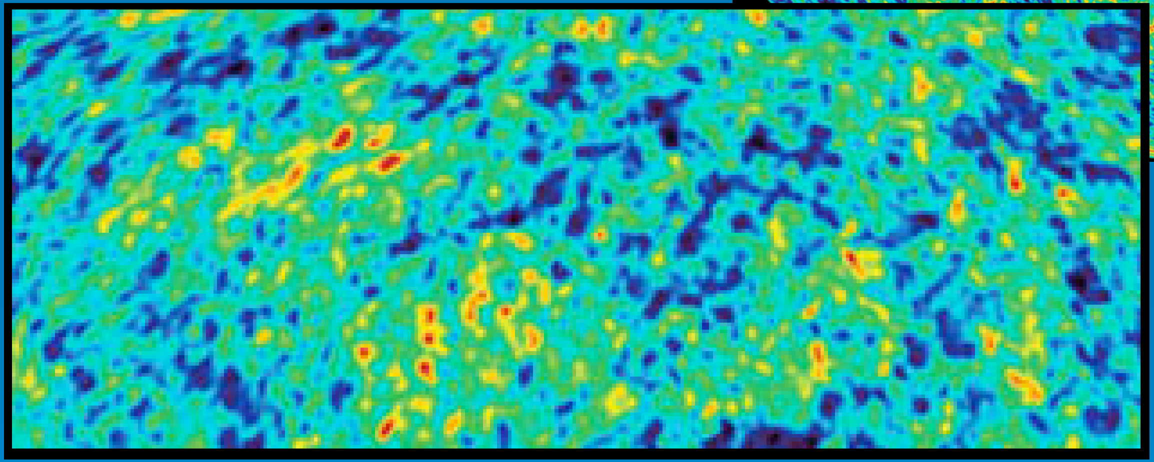
Daniel Eisenstein
University of Arizona

Outline

- Baryon acoustic oscillations as a standard ruler.
  - Acoustic oscillations in the non-linear regime.
- Detection of the acoustic signature in the SDSS Luminous Red Galaxy sample at z=0.35.
  - Cosmological constraints therefrom.
- Present the Baryon Oscillation Spectroscopic Survey and SDSS-III.

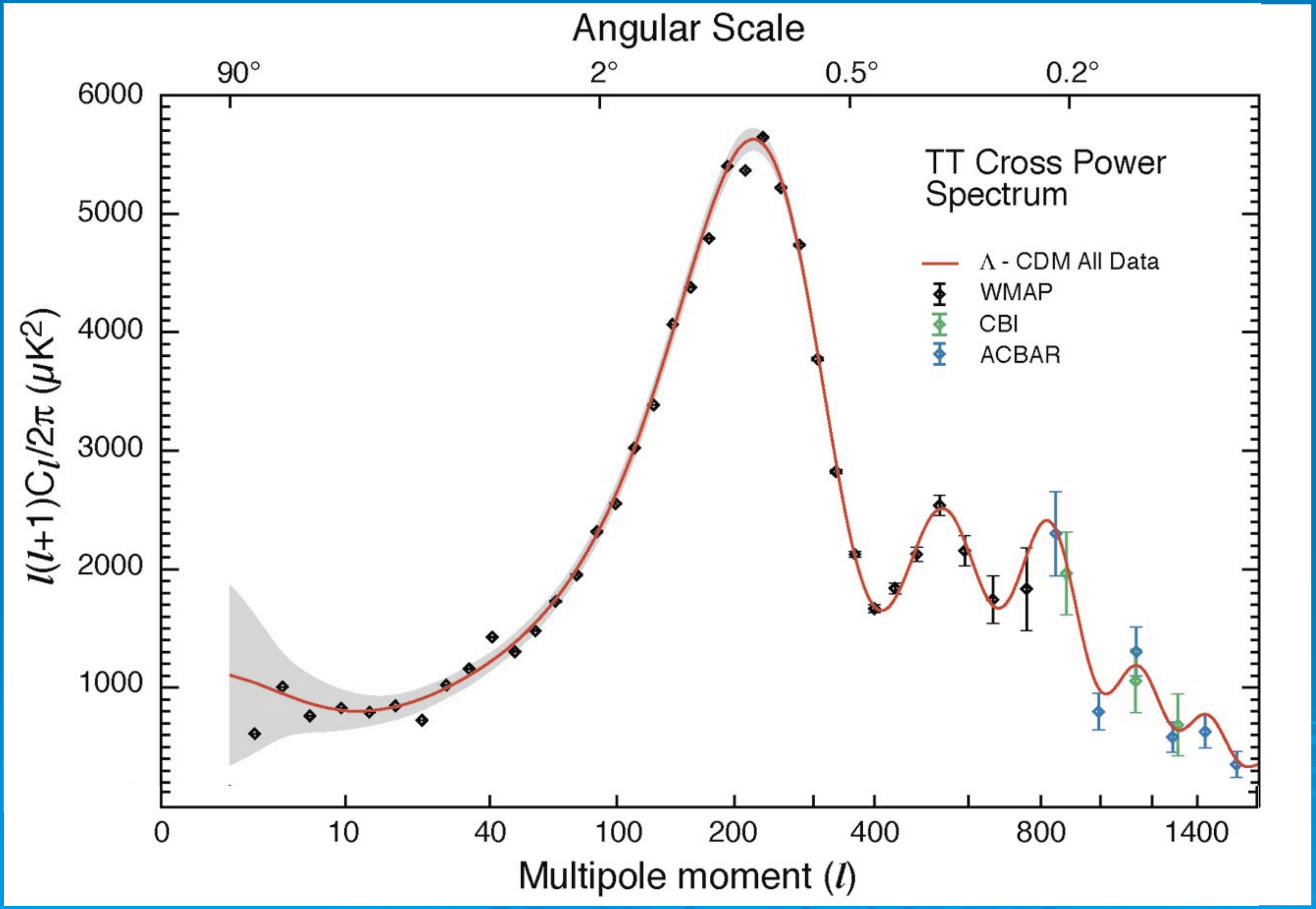
Acoustic Oscillations in the CMB





- Although there are fluctuations on all scales, there is a characteristic angular scale.

Acoustic Oscillations in the CMB



WMAP team (Bennett et al. 2003)

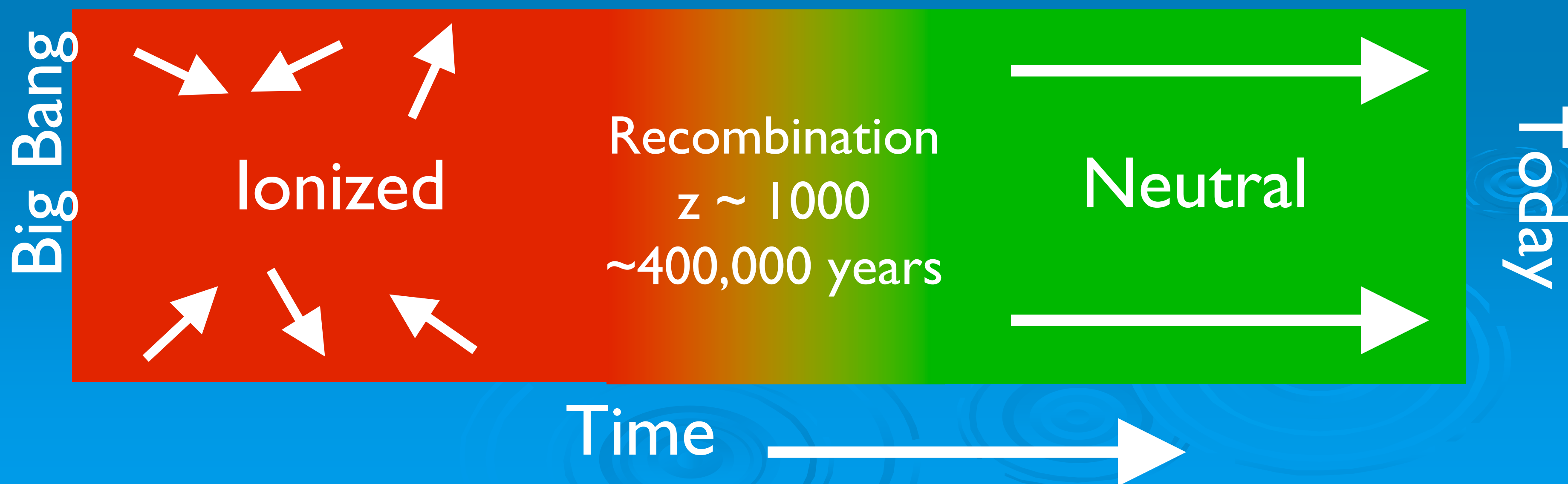
Sound Waves in the Early Universe

Before recombination:

- Universe is ionized.
- Photons provide enormous pressure and restoring force.
- Perturbations oscillate as acoustic waves.

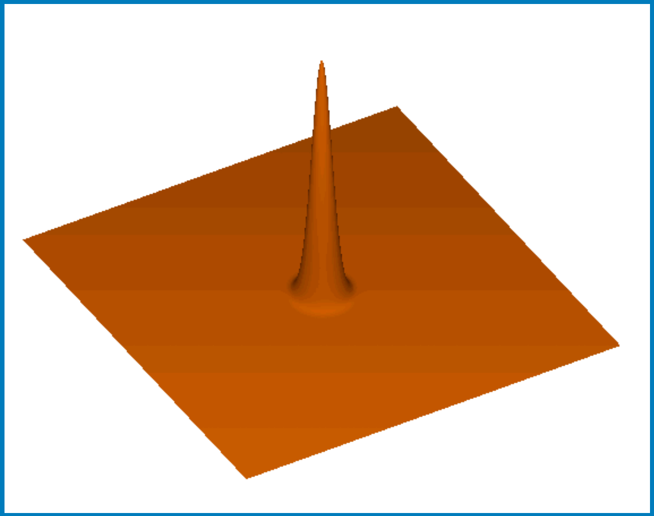
After recombination:

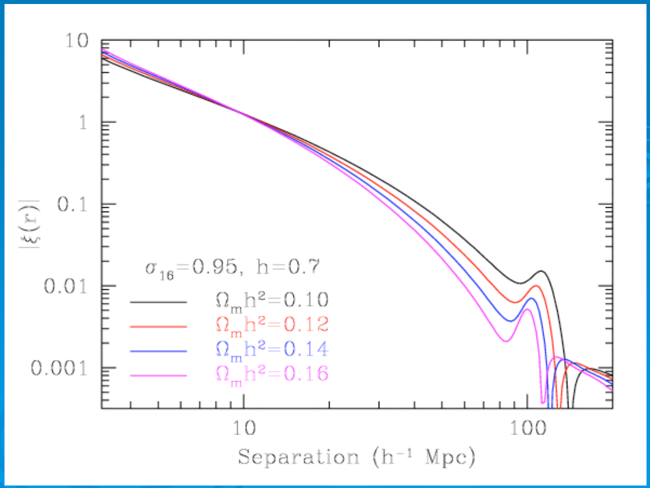
- Universe is neutral.
- Photons can travel freely past the baryons.
- Phase of oscillation at t_{rec} affects late-time amplitude.



Sound Waves

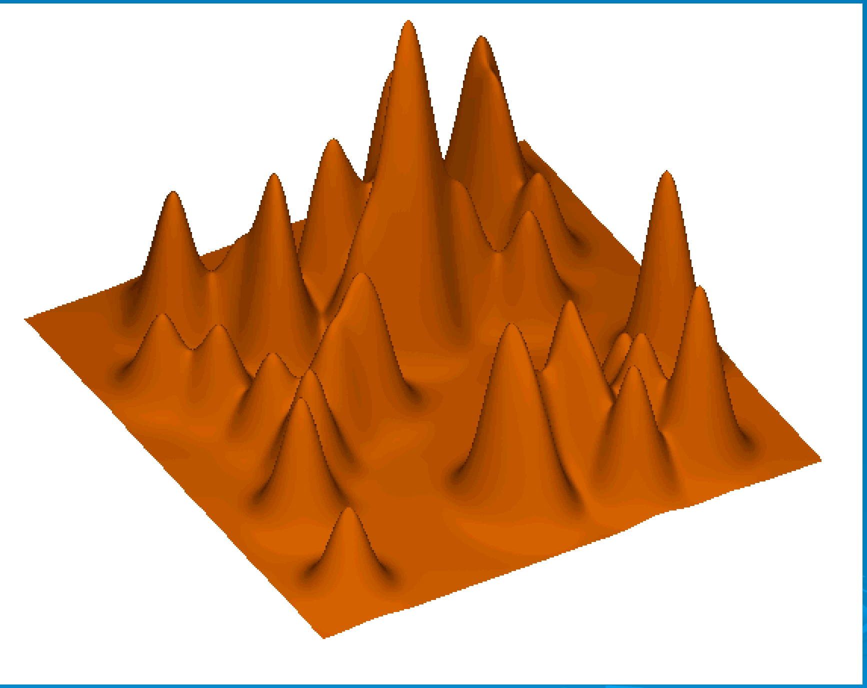
- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 150 Mpc.



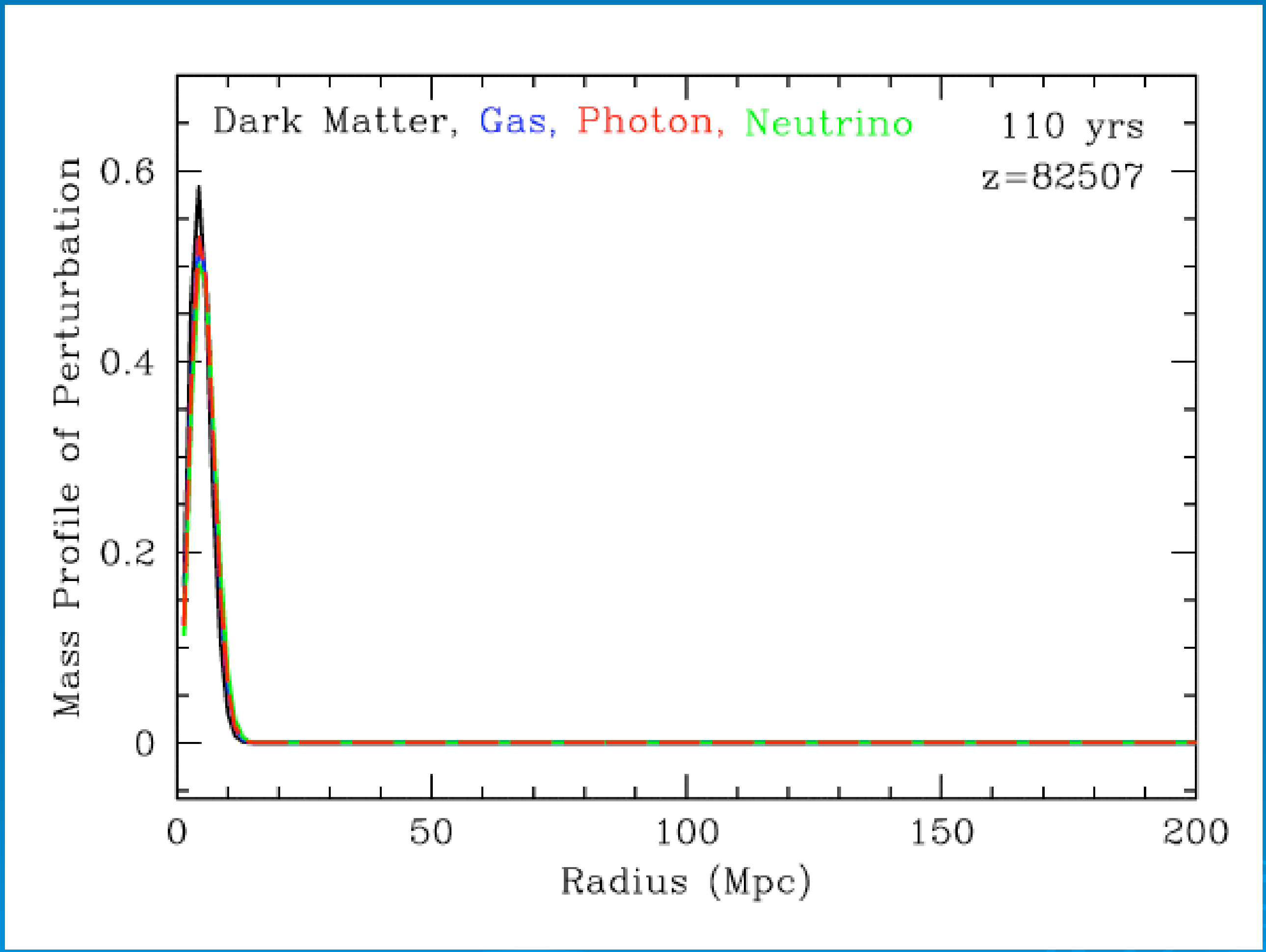


A Statistical Signal

- The Universe is a super-position of these shells.
- The shell is weaker than displayed.
- Hence, you do not expect to see bullseyes in the galaxy distribution.
- Instead, we get a 1% bump in the correlation function.



Response of a point perturbation

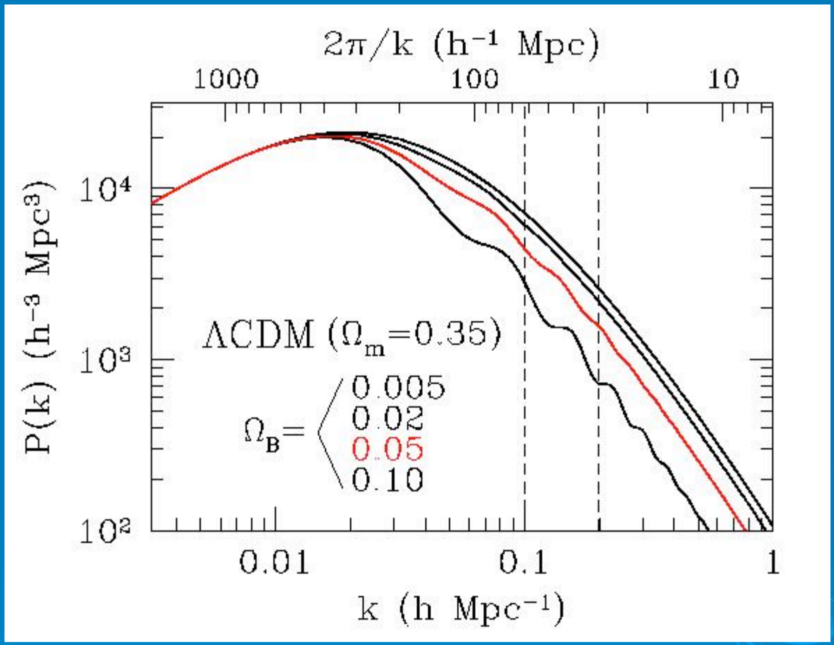


Remember: This is a tiny ripple on a big background.

Based on CMBfast outputs (Seljak & Zaldarriaga). Green's function view from Bashinsky & Bertschinger 2001.

Acoustic Oscillations in Fourier Space

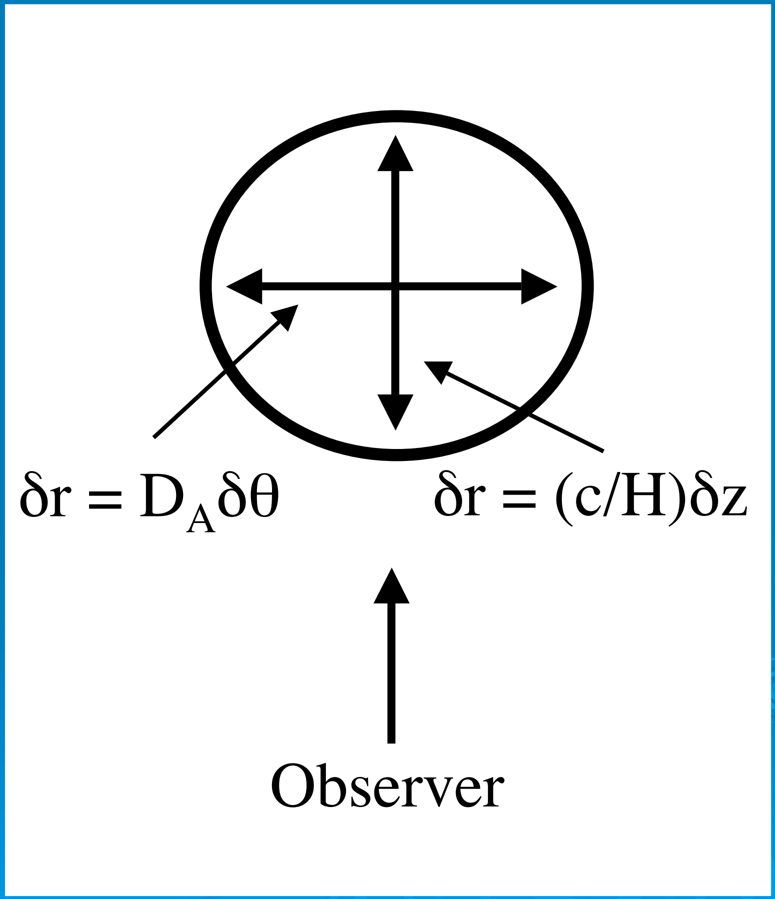
- A crest launches a planar sound wave, which at recombination may or may not be in phase with the next crest.
- Get a sequence of constructive and destructive interferences as a function of wavenumber.
- Peaks are weak — suppressed by the baryon fraction.
- Higher harmonics suffer from Silk damping.



Linear regime matter power spectrum

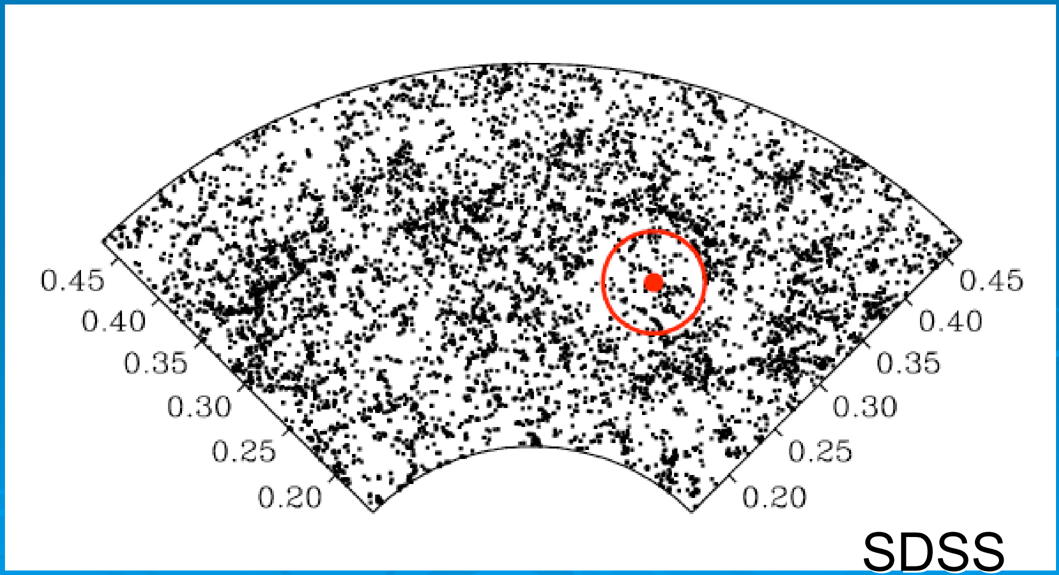
A Standard Ruler

- The acoustic oscillation scale depends on the sound speed and the propagation time.
  - These depend on the matter-to-radiation ratio ($\Omega_m h^2$) and the baryon-to-photon ratio ($\Omega_b h^2$).
- The CMB anisotropies measure these and fix the oscillation scale.
- In a redshift survey, we can measure this along and across the line of sight.
- Yields $H(z)$ and $D_A(z)$!



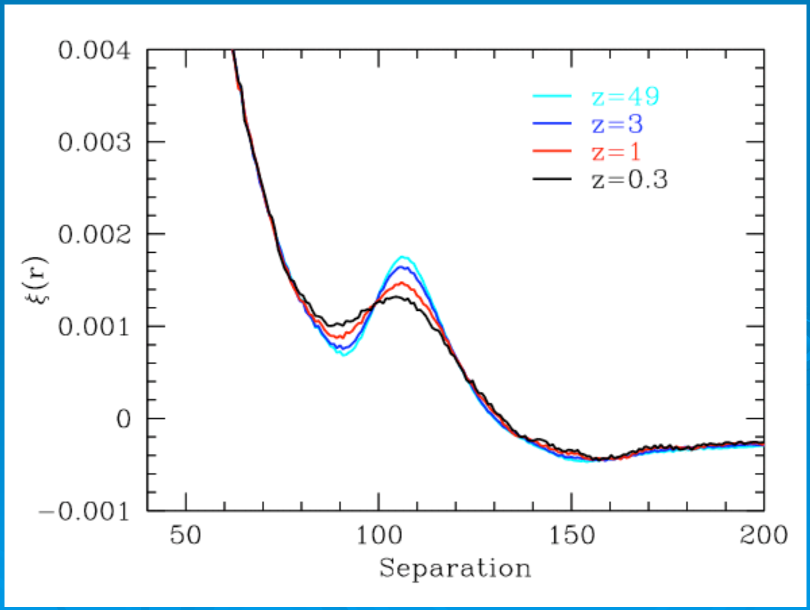
Galaxy Redshift Surveys

- Redshift surveys are a popular way to measure the 3-dimensional clustering of matter.
- But there are complications from:
  - Non-linear structure formation
  - Bias (light ≠ mass)
  - Redshift distortions
- Partially degrade the BAO peak, but systematics are small because this is a very large preferred scale.



Nonlinear Structure Formaton and the BAO

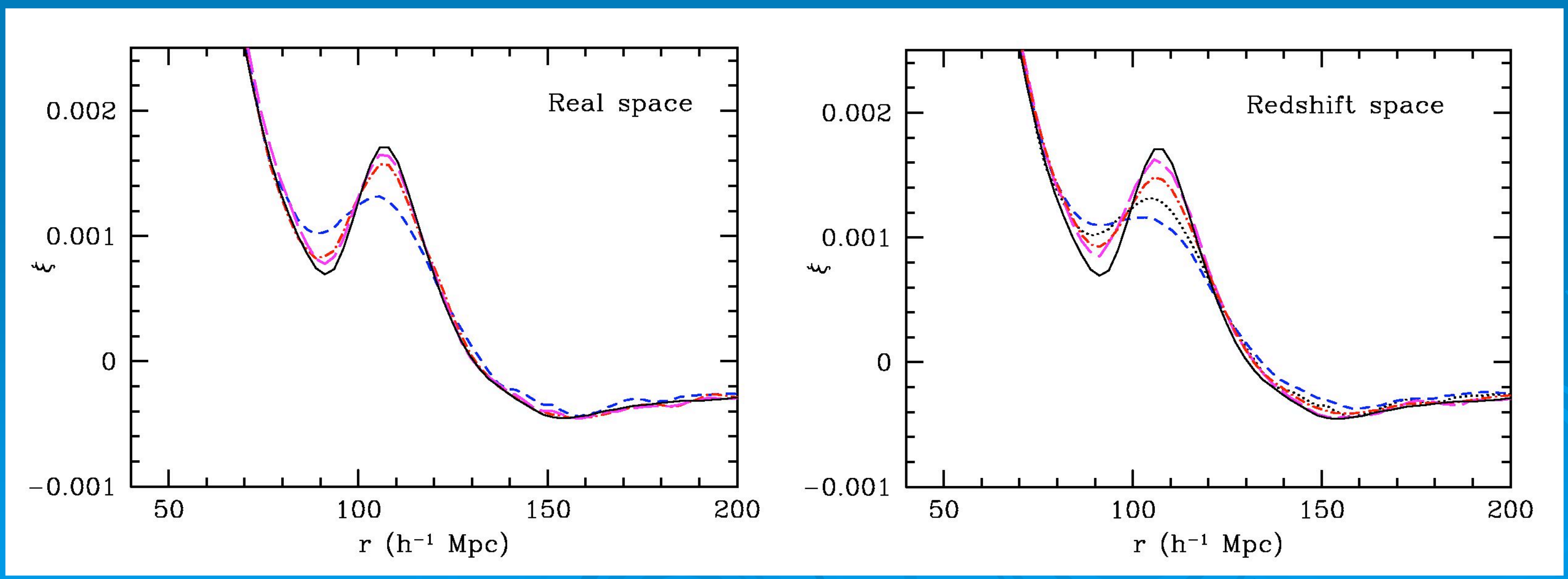
- The acoustic signature is carried by pairs of galaxies separated by 150 Mpc.
- Nonlinearities push galaxies around by 3-10 Mpc. Broadens peak, making it hard to measure the scale.
- Non-linearities are increasingly negligible at z>1. Linear theory peak width dominates.



Seo & DJE (2005); DJE, Seo, & White (2007)

Fixing the Nonlinearities

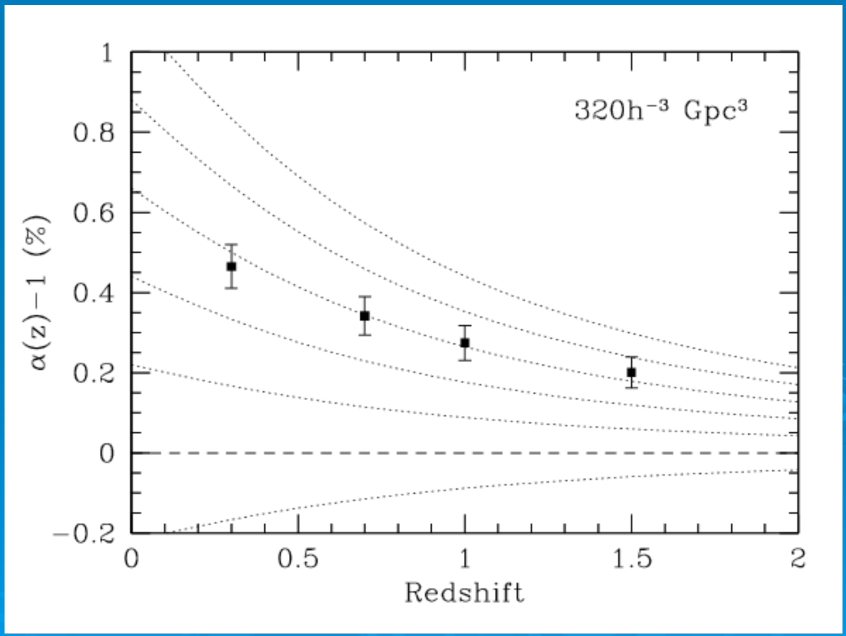
- Most of the non-linear degradation is due to bulk flows. These are produced by the same large-scale structure that we are measuring for the BAO signature.
- Map of galaxies tells us where the mass is that sources the gravitational forces that create the bulk flows.
- Can run this backwards and undo most non-linearity.
- Restore the statistic precision available per unit volume!



DJE, Seo, Sirko, & Spergel (2007)

Shifting the Acoustic Scale

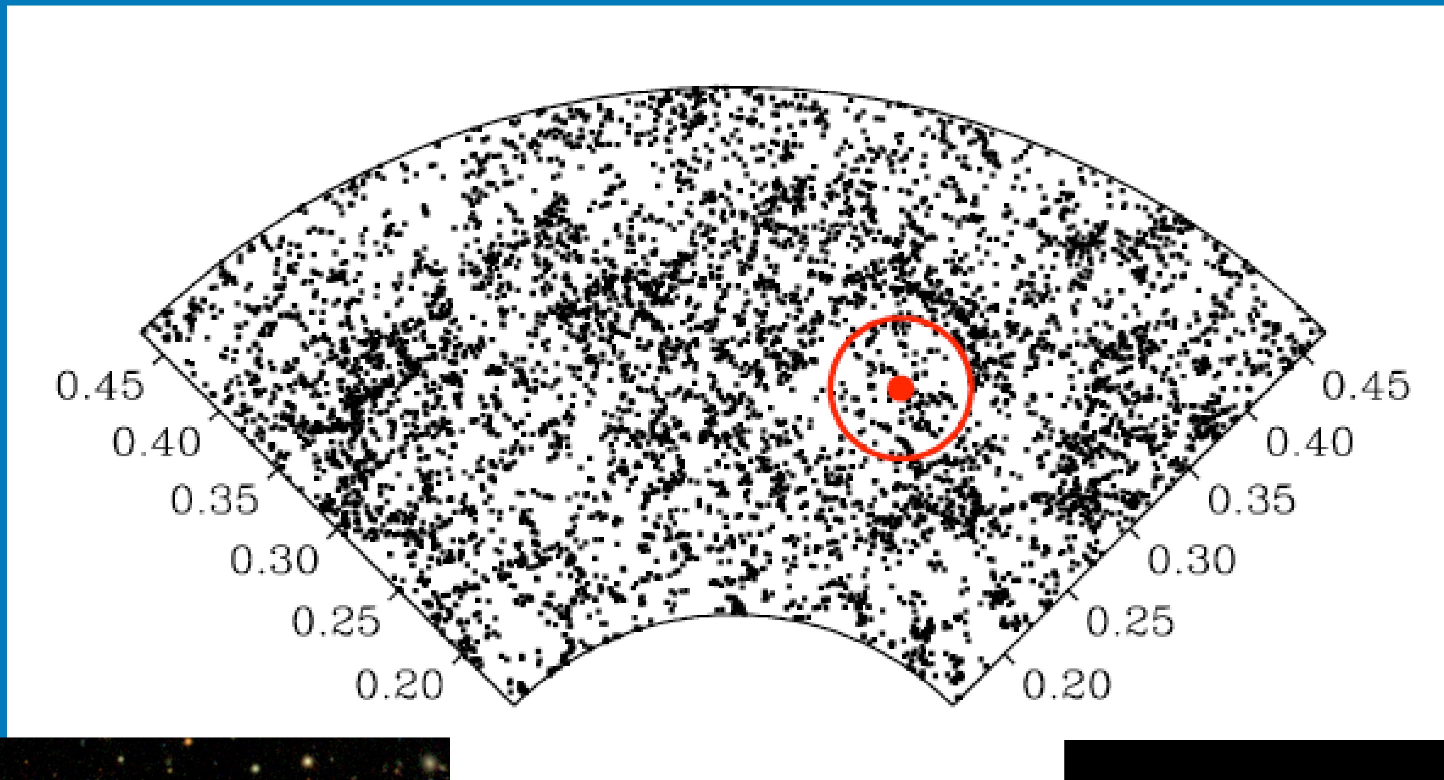
- Moving the acoustic scale requires net infall on 100 h^{-1} Mpc scales. Much smaller than random motions on small-scales. Expect infalls are <1%.
- We have used 320h^{-3} Gpc^3 of PM simulations to compute the non-linear shifts.
- Find shifts of 0.25% at z=1.5 to 0.5% at z=0.3.
- These shifts are predictable and hence removable! This is just large-scale gravitational flows.
- Galaxy bias enters through the relation of galaxies to these flows.

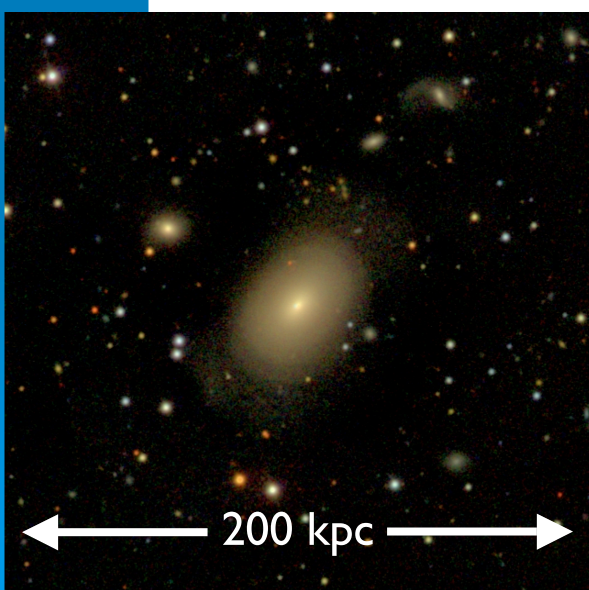


Seo, Siegel, DJE, & White (2008)

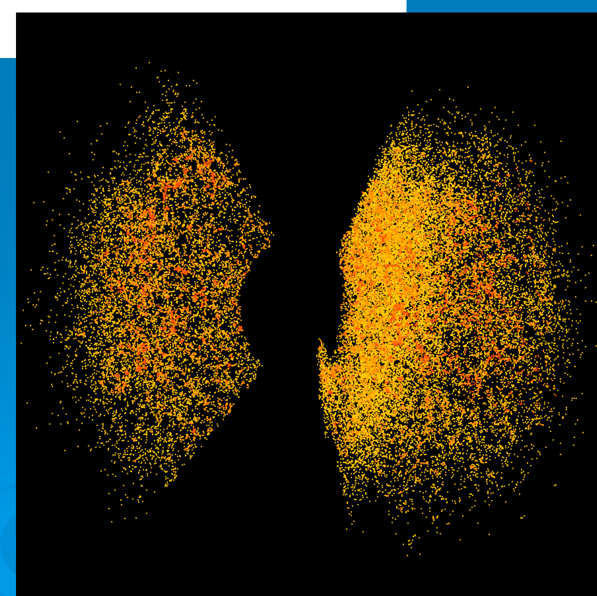
Virtues of the Acoustic Peaks

- The acoustic signature is created by physics at z=1000 when the perturbations are 1 in 10^4. Linear perturbation theory is excellent.
- Measuring the acoustic peaks across redshift gives a geometrical measurement of cosmological distance.
- The acoustic peaks are a manifestation of a preferred scale. Still a very large scale today, so non-linear effects are mild and dominated by gravitational flows that we can simulate accurately.
  - No known way to create a sharp scale at 150 Mpc with low-redshift astrophysics.
- Measures absolute distance, including that to z=1000.
- Method has intrinsic cross-check between $H(z)$ & $D_A(z)$, since D_A is an integral of H.

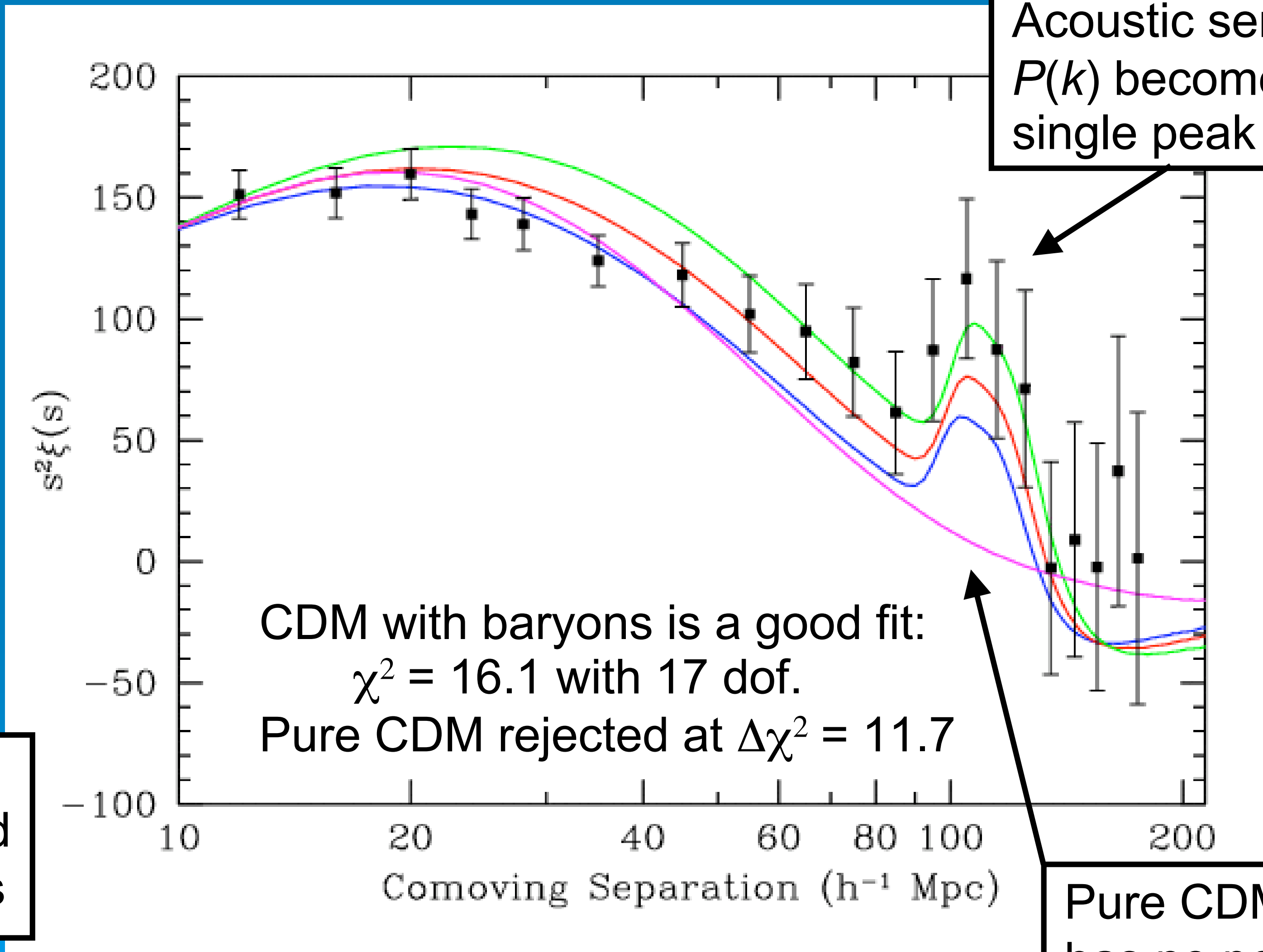




SDSS Luminous Red Galaxies



Large-Scale Correlations



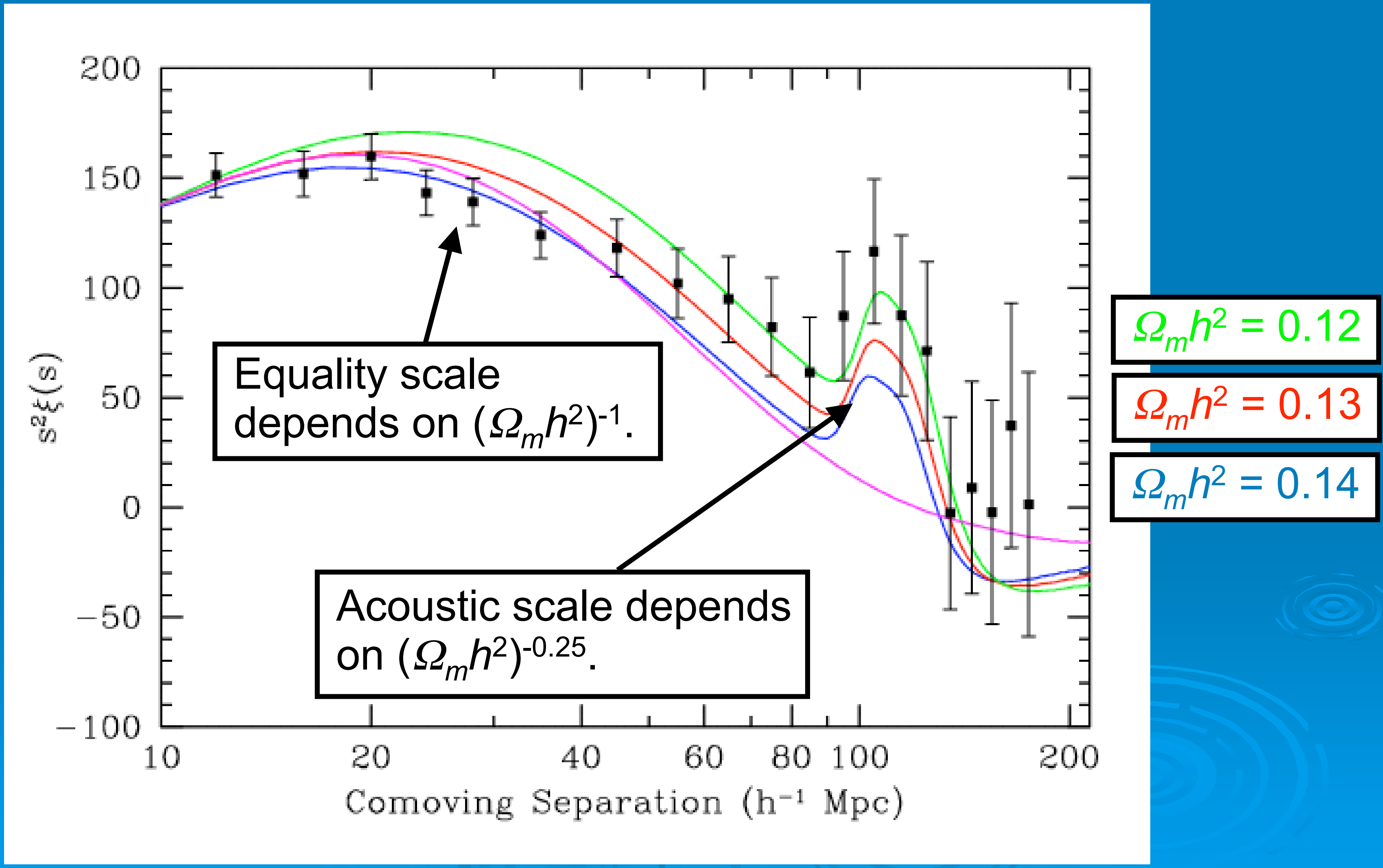
Acoustic series in $P(k)$ becomes a single peak in $\xi(r)$!

CDM with baryons is a good fit: χ^2 = 16.1 with 17 dof.
Pure CDM rejected at $\Delta\chi^2$ = 11.7

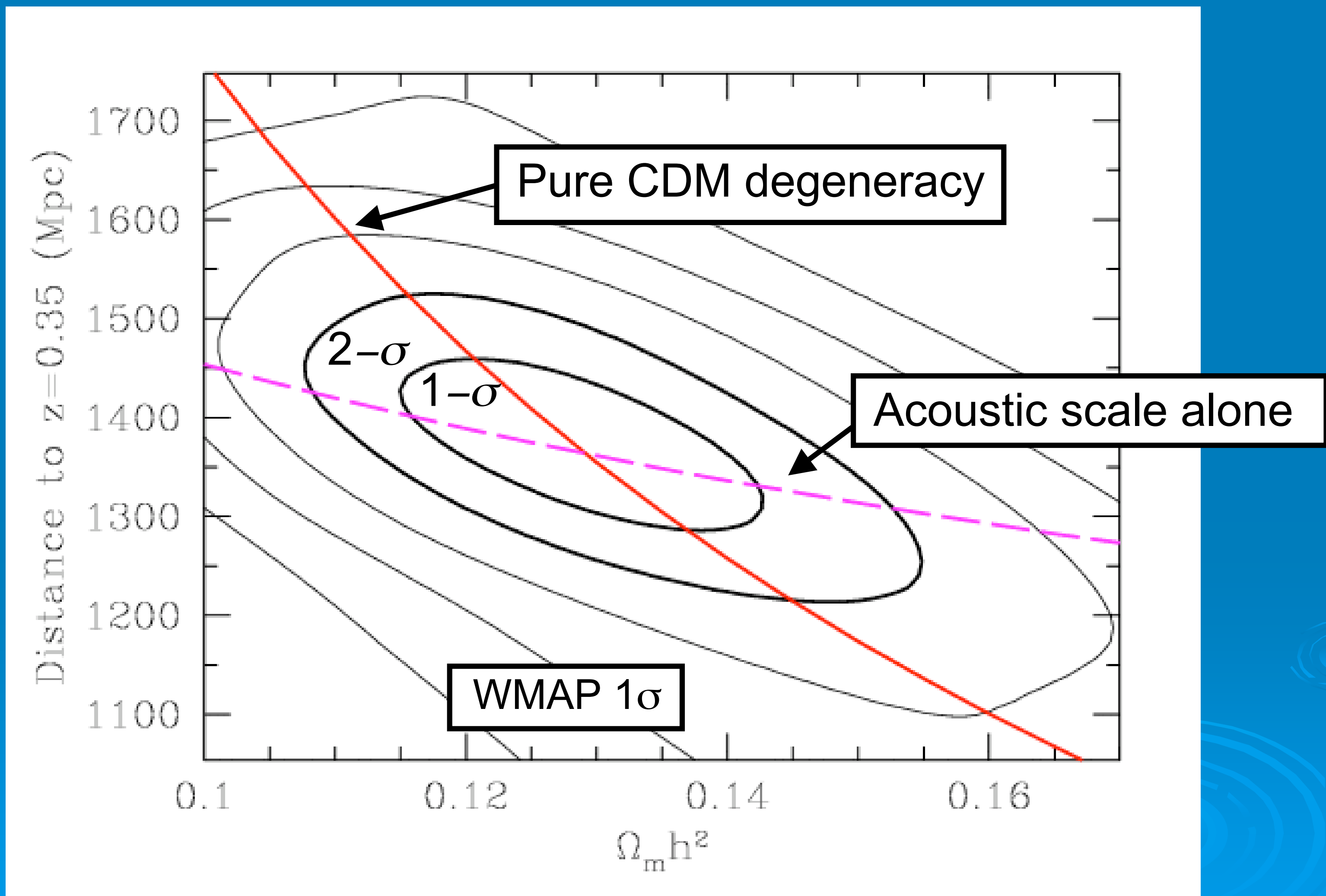
Pure CDM model has no peak.

Warning: Correlated Error Bars

Using the Standard Ruler



Cosmological Constraints

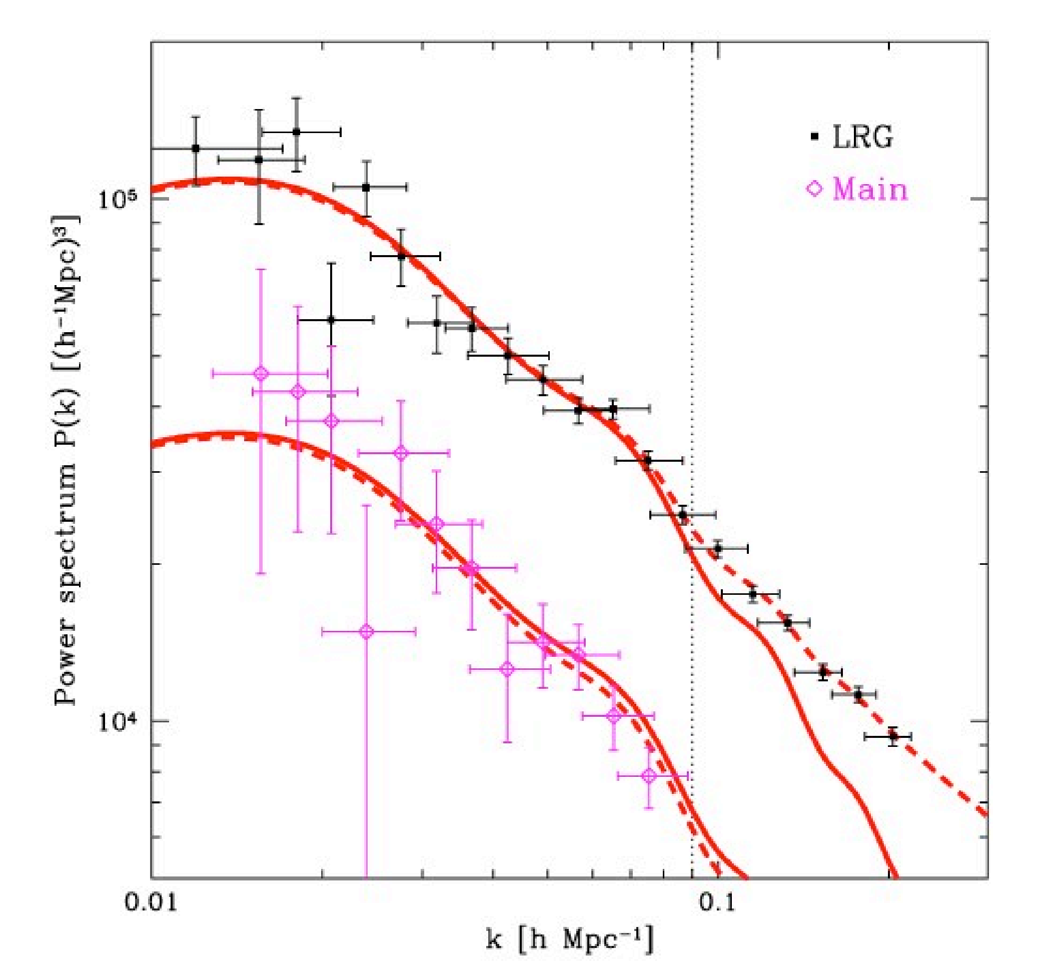


Essential Conclusions

- SDSS LRG correlation function does show a plausible acoustic peak.
- Ratio of $D(z=0.35)$ to $D(z=1000)$ measured to 4%.
  - This measurement is insensitive to variations in spectral tilt and small-scale modeling. We are measuring the same physical feature at low and high redshift.
- $\Omega_m h^2$ from SDSS LRG and from CMB agree. Roughly 10% precision.
  - This will improve rapidly from better CMB data and from better modeling of LRG sample.
- $\Omega_\mathrm{m} = 0.273 \pm 0.025 + 0.123(1+w_0) + 0.137\Omega_K$.

Power Spectrum

- We have also done the analysis in Fourier space with a quadratic estimator for the power spectrum.
- Also FKP analysis in Percival et al. (2006, 2007).
- The results are highly consistent.
  - Ω_m = 0.25, in part due to WMAP-3 vs WMAP-1.



Tegmark et al. (2006)

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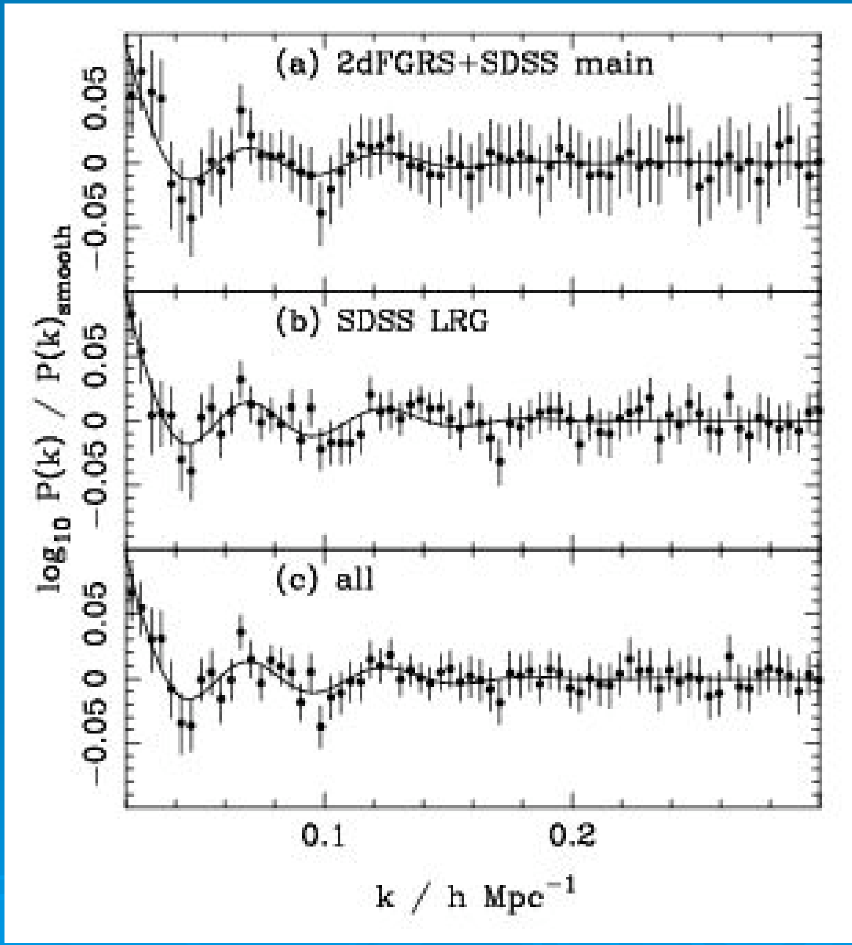


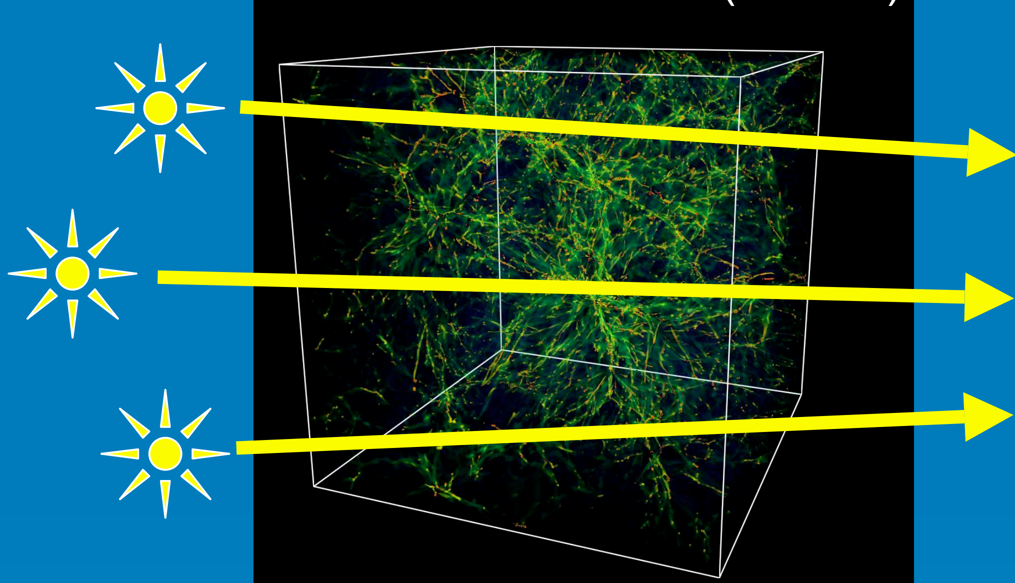
Percival et al. (2007)

Beyond SDSS

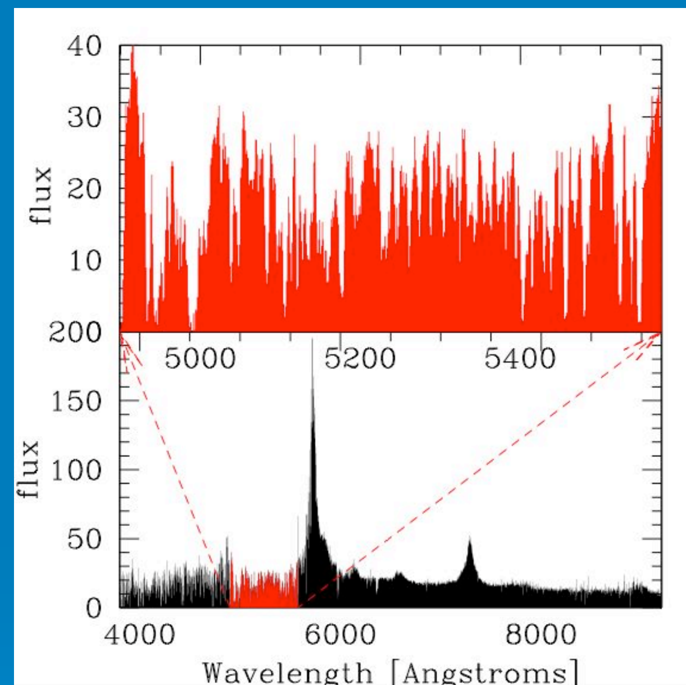
- By performing large spectroscopic surveys at higher redshifts, we can measure the acoustic oscillation standard ruler across cosmic time.
- Higher harmonics are at k~$0.2h$ Mpc^{-1} (λ=30 Mpc)
- Require several Gpc^3 of survey volume with number density few x 10^{-4} comoving h^3 Mpc^{-3}, typically a million or more galaxies!
- No heroic calibration requirements; just need big volume.

Seeing Sound in the Lyman α Forest

Neutral H simulation (R. Cen)



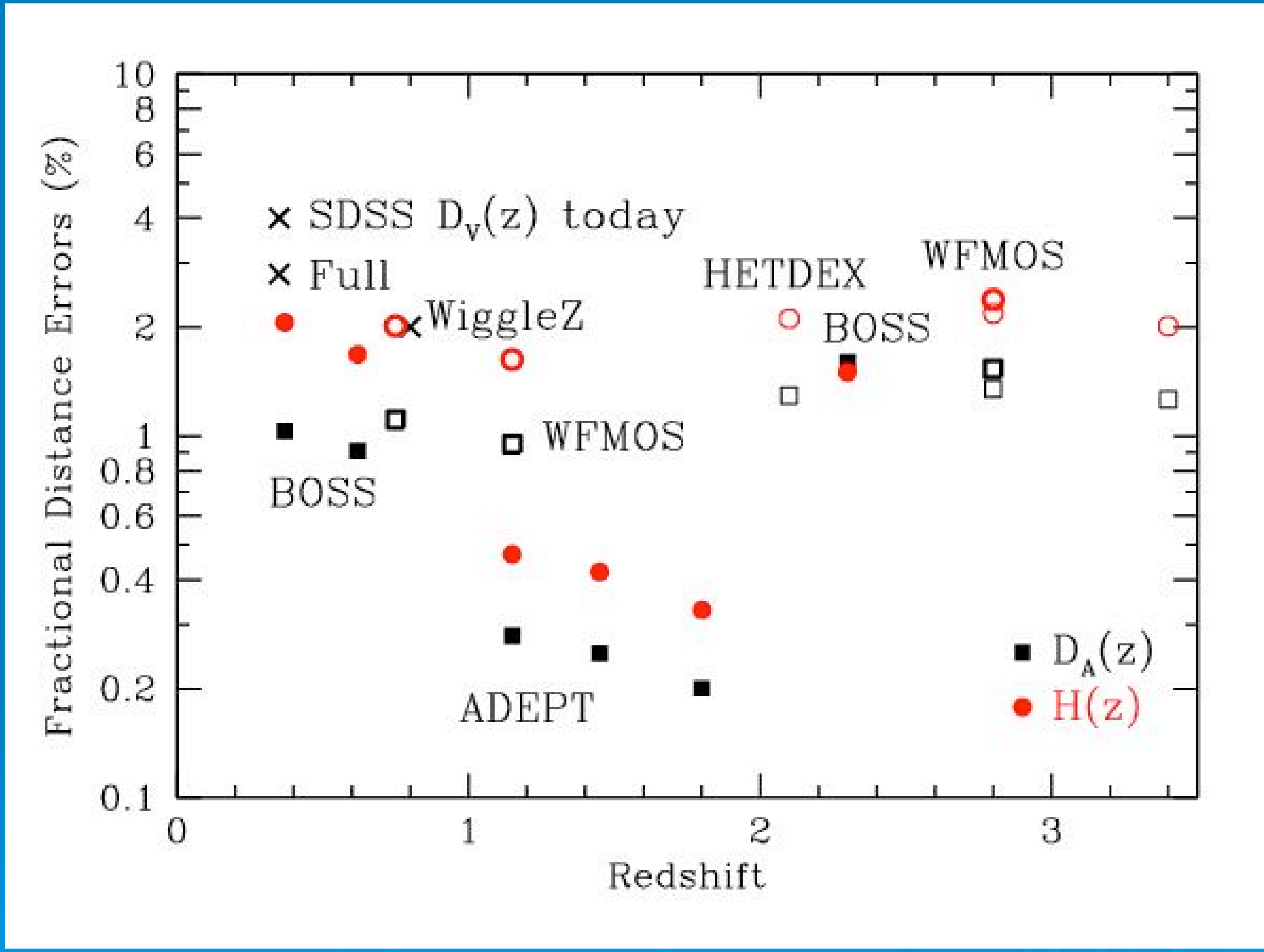
Neutral H absorption observed in quasar spectrum at z=3.7



- The Lyα forest tracks the large-scale density field, so a grid of sightlines should show the acoustic peak.
- This may be a cheapest way to measure the acoustic scale at *z*>2.
    - Require only modest resolution (R=250) and low S/N.
- Bonus: the sampling is better in the radial direction, so favors H(z).

White (2004); McDonald & DJE (2006)

Chasing Sound Across Redshift



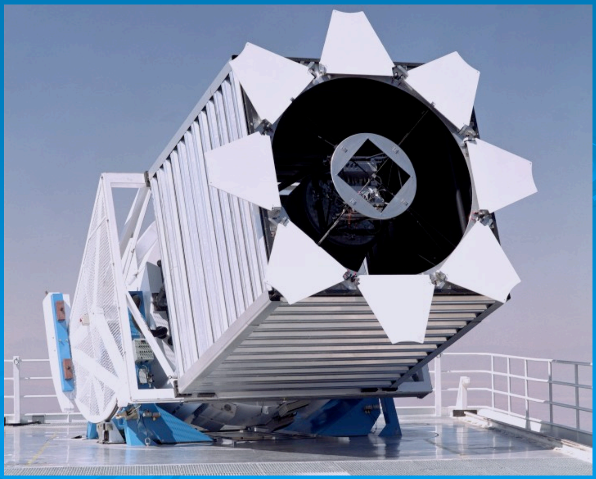
Distance Errors versus Redshift

SDSS-III

- SDSS-III will be the next phase of the SDSS project, operating from summer 2008 to summer 2014.
- SDSS-III has 4 surveys on 3 major themes.
  - BOSS: Largest yet redshift survey for large-scale structure.
  - SEGUE-2: Optical spectroscopic survey of stars, aimed at structure and nucleosynthetic enrichment of the outer Milky Way.
  - APOGEE: Infrared spectroscopic survey of stars, to study the enrichment and dynamics of the whole Milky Way.
  - MARVELS: Multi-object radial velocity planet search.
- Extensive re-use of existing facility and software.
- Strong commitment to public data releases.
- Collaboration is now forming.
  - Seeking support from Sloan Foundation, DOE, NSF, and over 20 member institutions.

Baryon Oscillation Spectroscopic Survey (BOSS)

- New program for the SDSS telescope for 2008–2014.
- Definitive study of the low-redshift acoustic oscillations. 10,000 deg^2 of new spectroscopy from SDSS imaging.
  - 1.5 million LRGs to z=0.8, including 4x more density at z<0.5.
  - 7-fold improvement on large-scale structure data from entire SDSS survey; measure the distance scale to 1% at z=0.35 and z=0.6.
  - Easy extension of current program.
- Simultaneous project to discover the BAO in the Lyman α forest.
  - 160,000 quasars. 20% of fibers.
  - 1.5% measurement of distance to z=2.3.
  - Higher risk but opportunity to open the high-redshift distance scale.



Cosmology with BOSS

- BOSS measures the cosmic distance scale to 1.0% at $z = 0.35$, 1.1% at $z = 0.6$, and 1.5% at $z = 2.5$. Measures $H(z = 2.5)$ to 1.5%.
- These distances combined with Planck CMB & Stage II data gives powerful cosmological constraints.
  - Dark energy parameters w_p to 2.8% and w_a to 25%.
  - Hubble constant H_0 to 1%.
  - Matter density Ω_m to 0.01.
  - Curvature of Universe Ω_k to 0.2%.
  - Sum of neutrino masses to 0.13 eV.
- Superb data set for other cosmological tests, as well as diverse extragalactic applications.

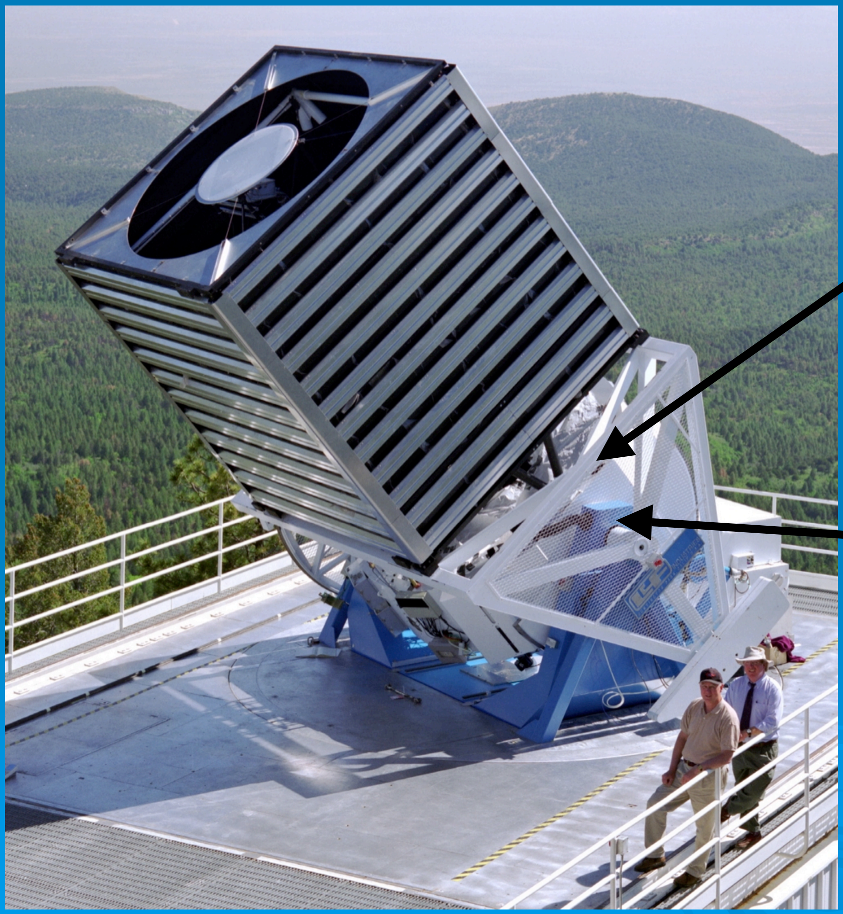
BOSS in Context

- DETF reports states that the BAO method is "less affected by astrophysical uncertainties than other techniques." Hence, BOSS forecasts are more reliable.
- BOSS is nearly cosmic-variance limited (quarter-sky) in its z < 0.7 BAO measurement.
  - Will be the data point that all higher redshift BAO surveys use to connect to low redshift. Cannot be significantly superceded.
  - WFMOS+BOSS produce a 1% BAO distance scale over range of z.
- BOSS will be the first dark energy measurement at z > 2.
- Moreover, BOSS complements beautifully the new wide-field imaging surveys that focus on weak lensing, SNe, and clusters.
  - BAO adds an absolute distance scale to SNe and extends to z > 1.
  - BAO+SNe are a purely $a(t)$ test, whereas WL and Clusters include the growth of structure as well. Crucial opportunity to do consistency checks to test our physical assumptions.

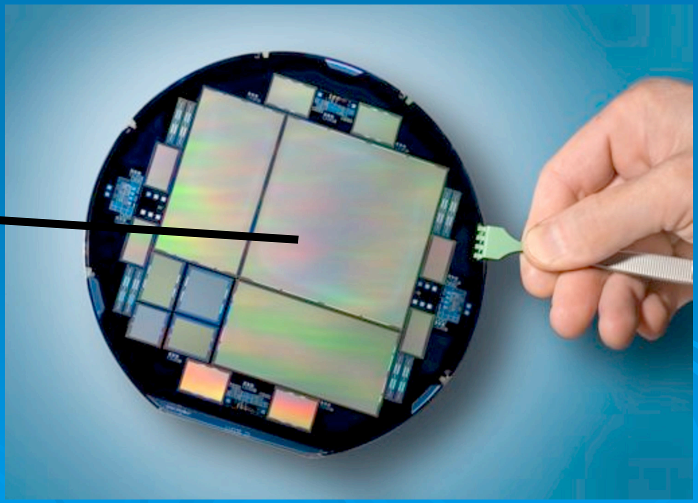
BOSS Instrumentation

- Straightforward upgrades to be commissioned in summer 2009

SDSS telescope + most systems unchanged



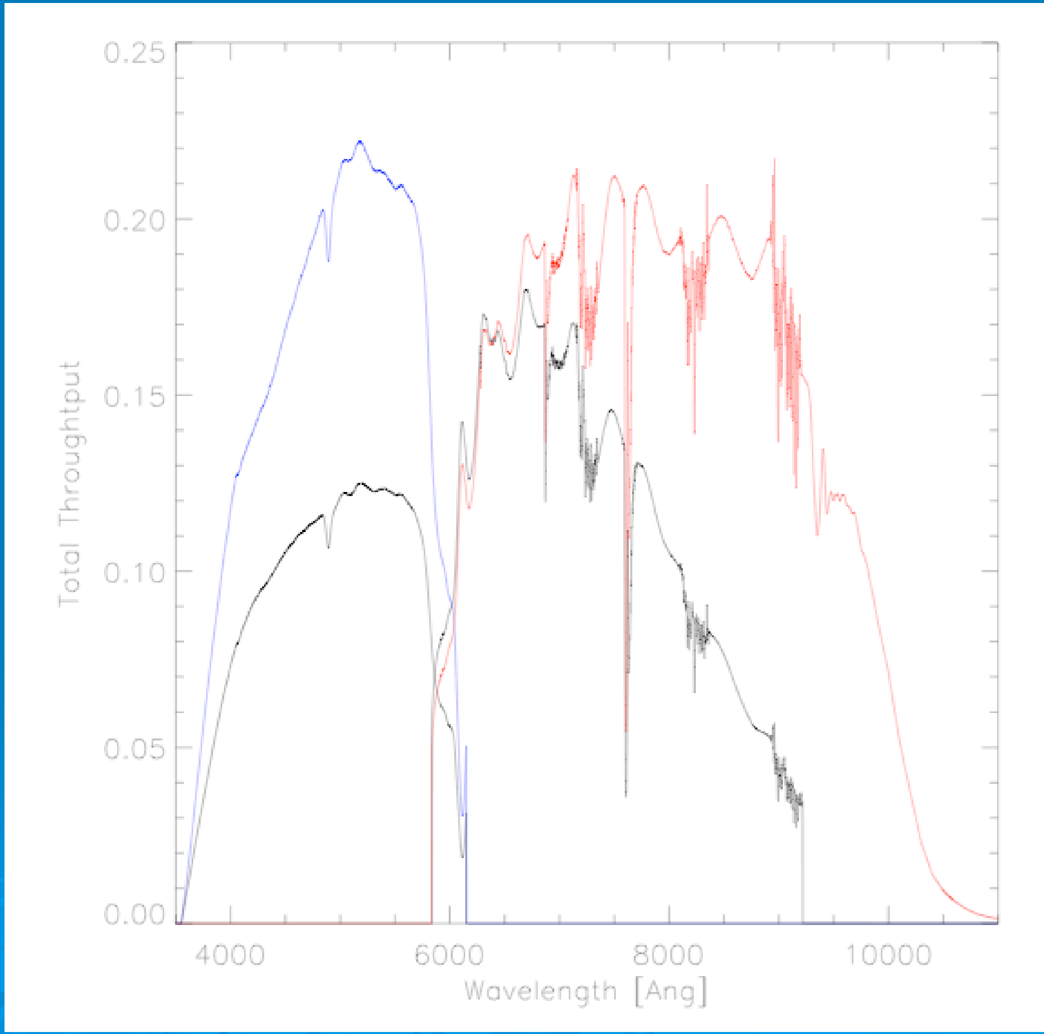
1000 small-core fibers to replace existing (more objects, less sky contamination)



LBNL CCDs + new gratings improve throughput
Update electronics + DAQ

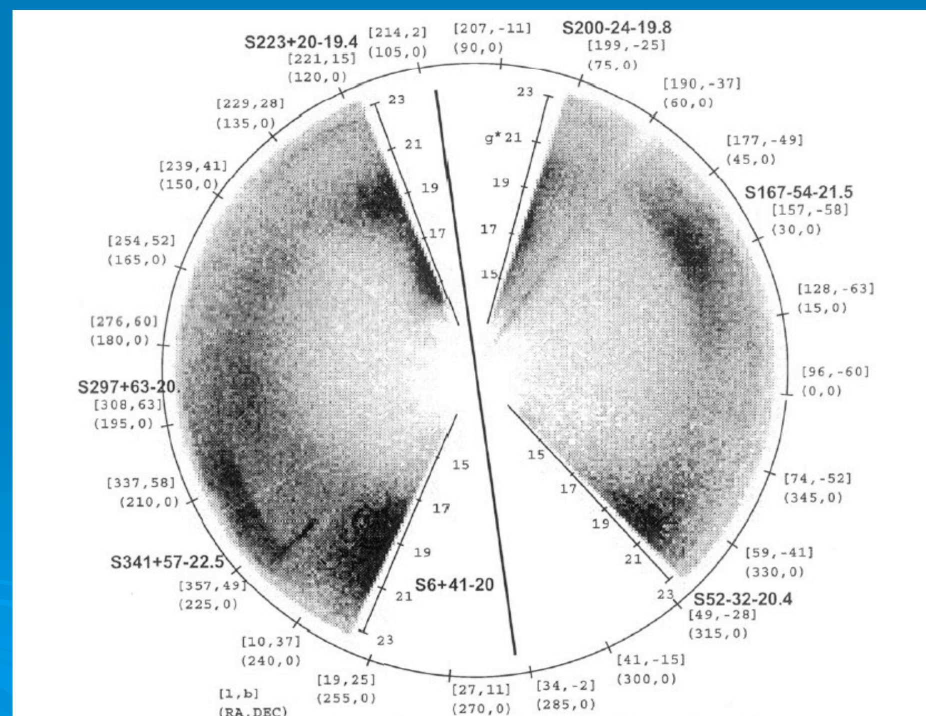
System Throughput

- Total throughput, including atmosphere, telescope, “slit” losses.
- Neglecting slit losses, existing SDSS peaks at 25%.
- BOSS is nearly a factor of two better at 5000A and 8000A.
- Fiber systems do not have low throughput!



Assembly of the Milky Way

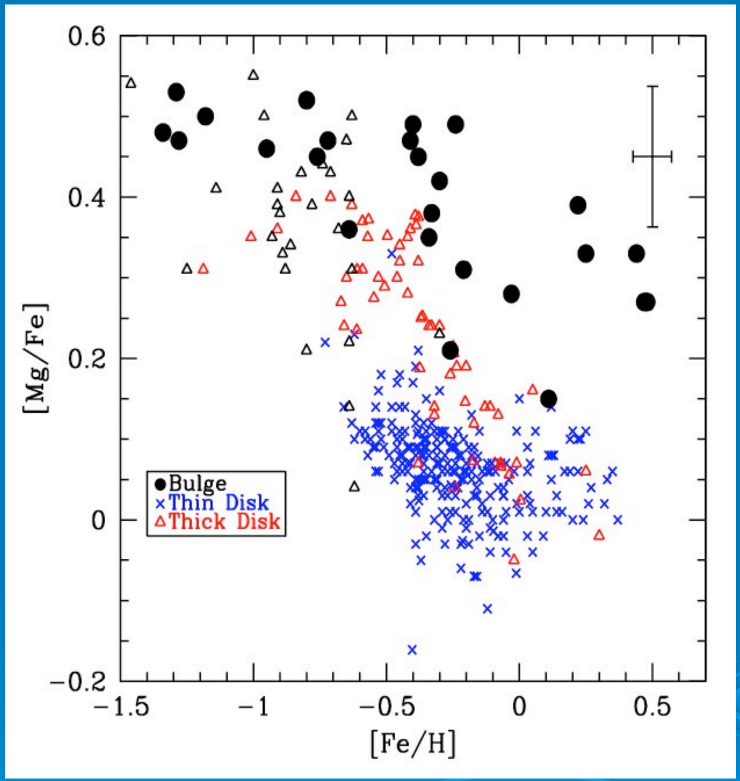
- The last decade has shown that the Milky Way is lumpy and complex.   Not the textbook version!
- Stellar motions show the buildup from many small systems.
- These merger events leavelong-lasting signatures. We are dissecting the Milky Way in time as well as space.



Density of the Outer Halo from SDSS (Newberg et al. 2004)

Abundances of Elements

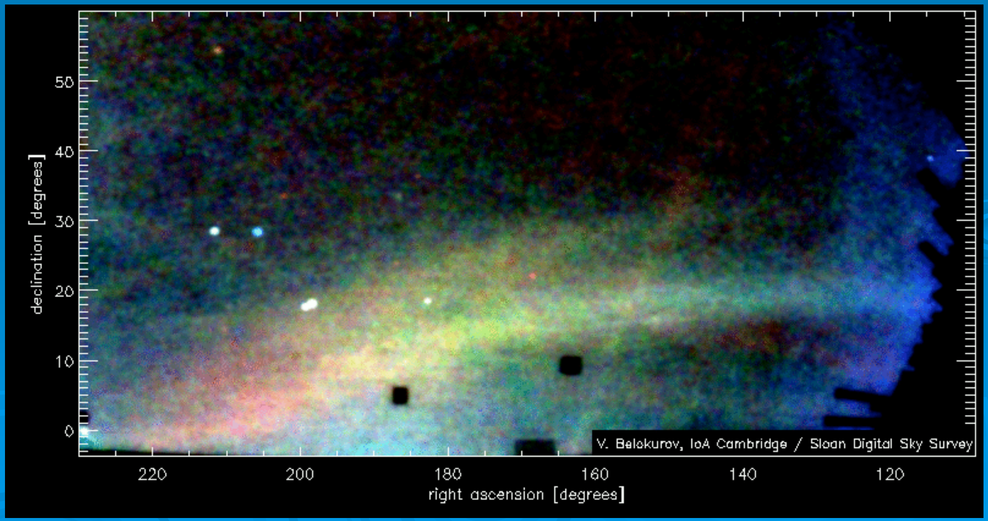
- Chemical mix in stars tells us about the properties of their ancestors. A window into the early phases of the Galaxy—a second probe of assembly.
  - Heavy element production is a strong function of type of star.
  - Not just a 1 or 2 parameter family; each element has a story to tell.
- More dramatically, this is the study of how the elements (and hence Earth and us) came to be.



Example: the Milky Way bulge formed quickly, less than 10^9 yr. (Fulbright et al. 2006)

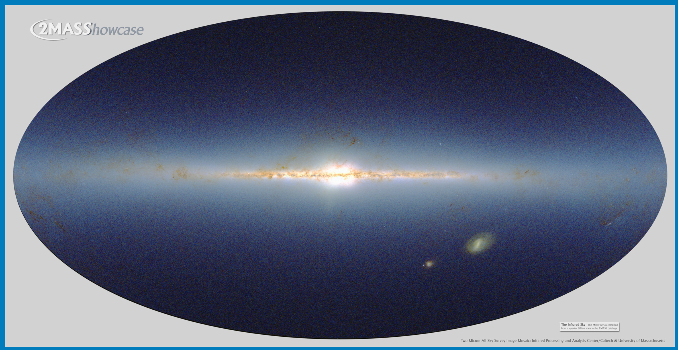
SEGUE-2: Probing the Outer Milky Way

- SEGUE-2 will map the dynamical and nucleosynthetic history of the thick disk and halo.
  - 250,000 optical spectra of faint stars in year 1.
  - Over 100,000 spectra of brighter stars in years 2-6.
- Discovery & exploration of tidal streams.
- Explore the outer halo of the Milky Way, which has bulk differences compared to the inner halo.
- Find the rarest, least enriched stars for clues about the earliest supernovae.



APO Galaxy Evolution Explorer:
Unveiling the Inner Milky Way

- The thin disk and inner bulge of the Milky Way are obscured by interstellar dust. Need infrared observations to reveal it.



- There is an enabling coincidence between the luminosity of red giant stars in the galactic bulge, the depth of 2MASS imaging, and the light collecting power of a 2.5-meter telescope.
  - In 1-3 hour exposures, we can acquire S/N=100 spectra at R=20,000 in the H-band on red giant stars out to 25 kpc.
  - Can access the inner galaxy (and a fair bit of the halo) with the kind of spectra required for detailed element abundance analyses and sub-km/s velocity precision.
  - Red giants can be selected from 2MASS; whole sky is available.

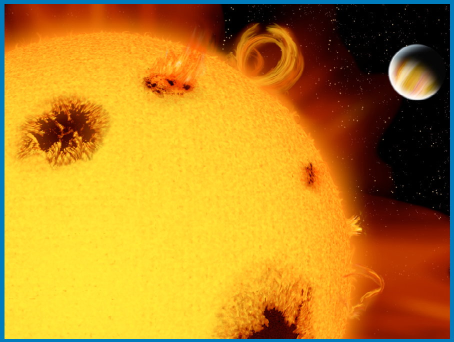
APOGEE

- APOGEE will study the whole Galaxy with a new high-resolution infrared (1.6 μm) spectrograph.
  - 300 fibers, R=20,000 to cleanly separate lines.
  - Abundances of over 10 elements, including C, N, O.
  - Unique instrument: First multiobject work at this resolution in the IR.
  - 1.5-1.7 μm permits work with warm fibers. IR detectors finally large enough to get significant spectral range.
- Ground-breaking sample of 100,000 stars.
- Common abundance scale across all parts of Galaxy.

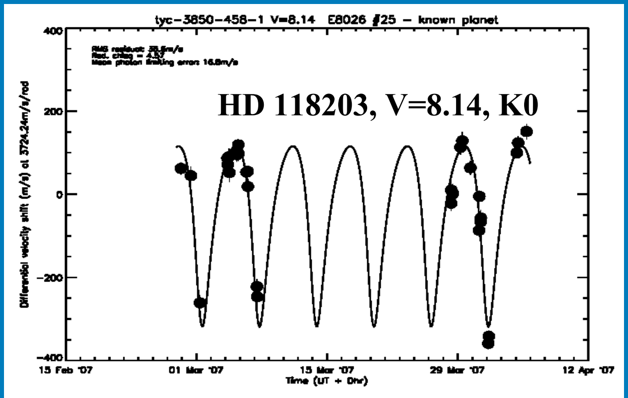
SEGUE-2 and APOGEE in Context

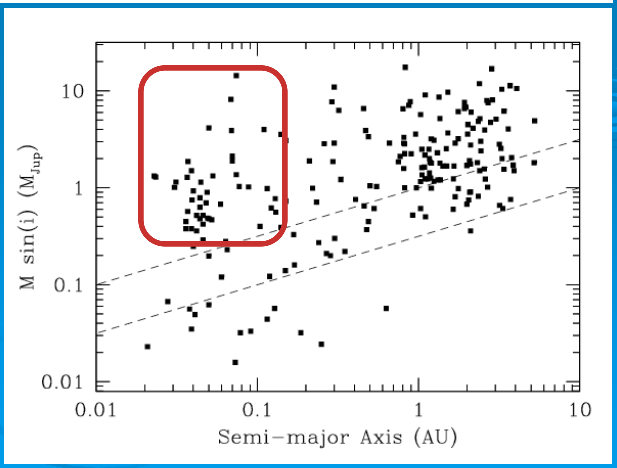
- SEGUE-2 is a short-term extension of our successful ongoing program.
  - Much fainter than RAVE and GAIA spectroscopy; can probe the chemical and dynamical halo.
- APOGEE is a superb complement to GAIA.
  - Yields high-resolution abundances of many elements, to match with GAIA astrometry.
  - Probes inner Galaxy and puts full Galaxy on a common abundance scale.
- APOGEE is a superb complement to WFMOS.
  - Infrared coverage of the inner Galaxy.
  - Infrared and optical offer different sets of elements.

Extrasolar Planets



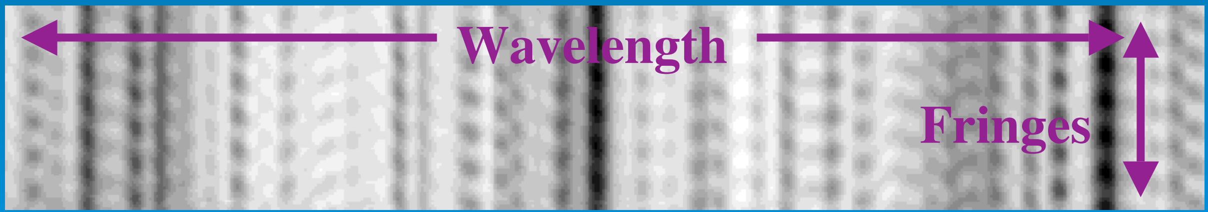
- In the last 12 years, about 200 planets have been discovered around other stars.
  - Nearly all due to measuring Doppler shift caused by reflex motion of the star.
  - Requires precision <10 m/s.
- Significant surprises, such as the presence of massive planets very close to their stars (super-Jupiters inside Mercury's orbit) and the high eccentricity of those planets. Planet formation is still poorly understood.
- Current planet searches are hetero-geneous. The available statistical samples are small, making it difficult to test planet formation theories.



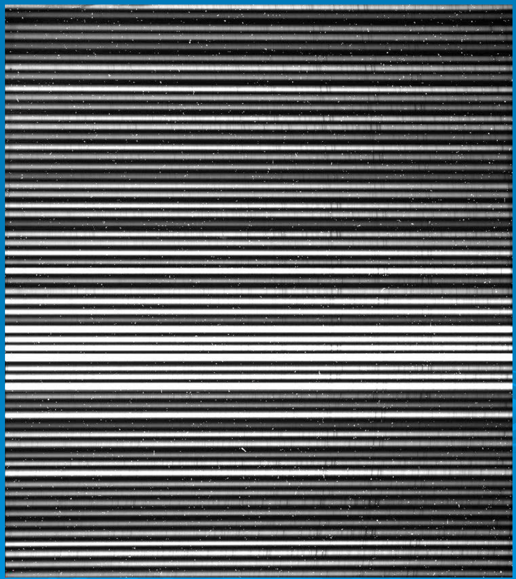


Innovative Instrumentation

- Current planet searches have all been one star at a time, using lots of telescope time. To go significantly further will require multi-object techniques.
- Keck Extrasolar Tracker (KET) uses a dispersed interferometer to allow us to survey 60 stars at once. Already working at APO 2.5-meter.
- The SDSS telescope has a wide enough field of view to observe hundreds of bright stars simultaneously.



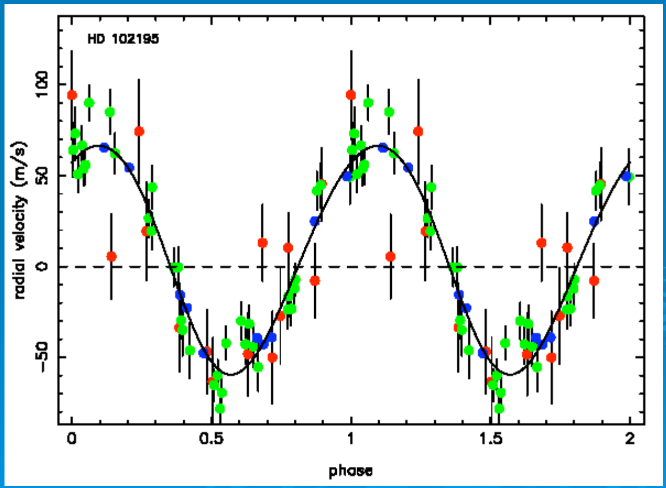
Cross-dispersed interferometric fringes carry the velocity information.
Erskine & Ge (2000), Ge et al. (2002), Ge (2002).



60 simultaneous spectra with existing KET at APO 2.5-meter.

Multi-object APO Radial-Velocity Exoplanet Large-area Survey

- MARVELS will conduct a systematic survey of 11,000 stars, looking for Jupiter-mass planets at periods from 1 to 500 days.
  - Use 2 ET instruments to monitor the radial velocities of over 100 stars per pointing, magnitudes 8<V<12.
  - Not biasing to high metallicity stars.
- Expect to discover more than 200 planets, including rare cases.
- Unbiased demographics of massive planet formation.
- Full reporting of selection function to allow statistical testing of theories, e.g. planet frequency vs period, mass, & stellar metallicity.



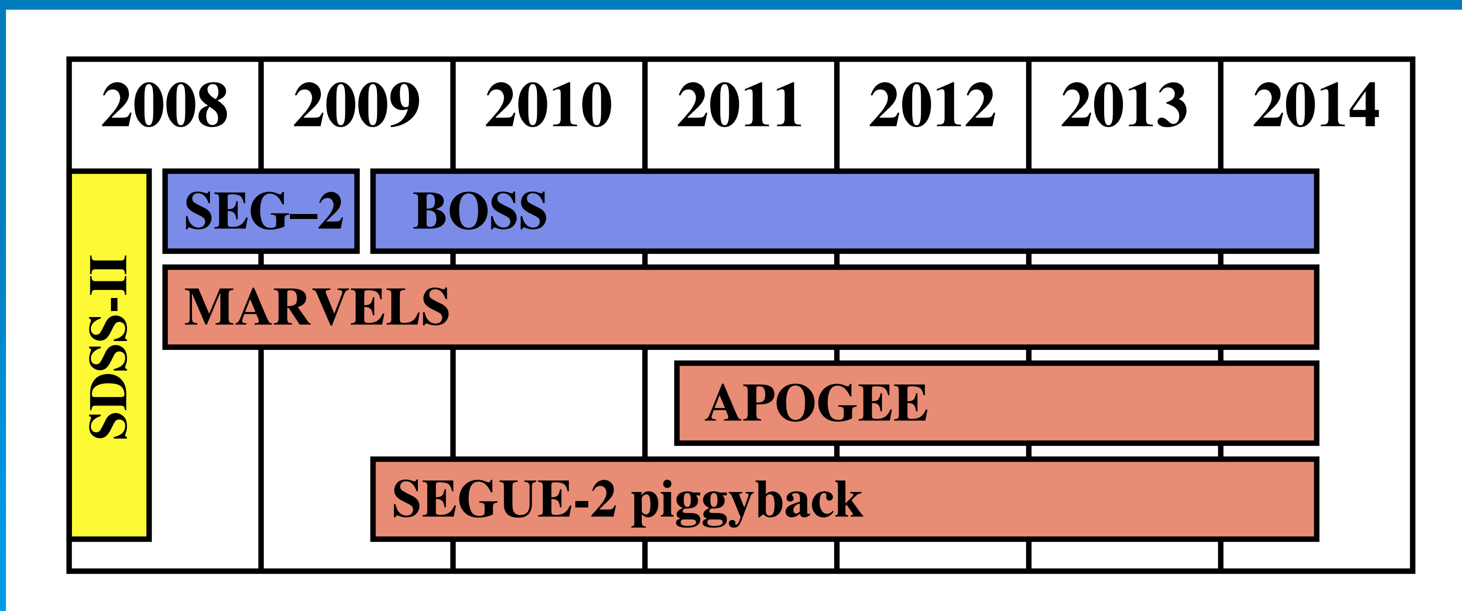
First ET planet discovery
(Ge et al. 2006)

MARVELS in Context

- MARVELS will not reach the velocity precision of the single-object radial velocity programs (RPF, HARPS, etc.), but it will target many more stars.
  - Other systems will probe Neptune-mass planets around 1000-2000 stars.
  - MARVELS will study the rarer Jupiter-mass planets around 10^4 stars.
- Full demographic study. ~30 epochs per star so that one can characterize each system and quantify the selection function.
  - Single-object systems tend to pick and choose more, valuing pushing the envelope more than statistical samples.
- Transit searches (like Kepler) excel at <10 day periods; astrometric searches (like GAIA) excel at multi-year periods; direct detection at longer yet. Radial velocity searches have a critical position in the study of planet migration.
- MARVELS discoveries will be fertile ground for followup with high-precision, single-object instruments, searching for more planets in these systems.

Four Surveys Together

- SEGUE-2 & BOSS use moonless time. MARVELS & APOGEE use moony time.
- MARVELS and APOGEE will share the focal plane, along with a SEGUE-2 piggyback program. One common fiber cartridge, with all fibers active.
- Six years of observations, plus development time.



SDSS-III Likely Partners

- Univ. of Arizona
- Brazilian Participation Group
- Cambridge Univ.
- Canadian Participation Group
- Case Western Univ.
- Univ. of Florida
- French Participation Group
- Univ. of Heidelberg
- Japanese Participation Group/IPMU
- Johns Hopkins Univ.
- Korean Institute for Advanced Study
- Lawrence Berkeley Lab
- Los Alamos National Lab
- MPA Garching
- MPE Garching
- MPIA Heidelberg
- Michigan State Univ/JINA
- New Mexico State Univ.
- New York Univ.
- Ohio State Univ.
- Penn State Univ.
- Univ. of Portsmouth
- Astronomical Institute Potsdam
- Princeton Univ.
- Univ. of Utah
- Univ. of Virginia
- Univ. of Washington
- Plus a number of individuals

We've Only Just Begun

- SDSS LRG has only surveyed only 10^{-3} of the volume of the Universe out to z~5.
- Only 10^{-4} of the modes relevant to the acoustic oscillations.
- Fewer than 10^{-6} of the linear regime modes available.
- There is an immense amount more information about the early Universe available in large-scale structure.

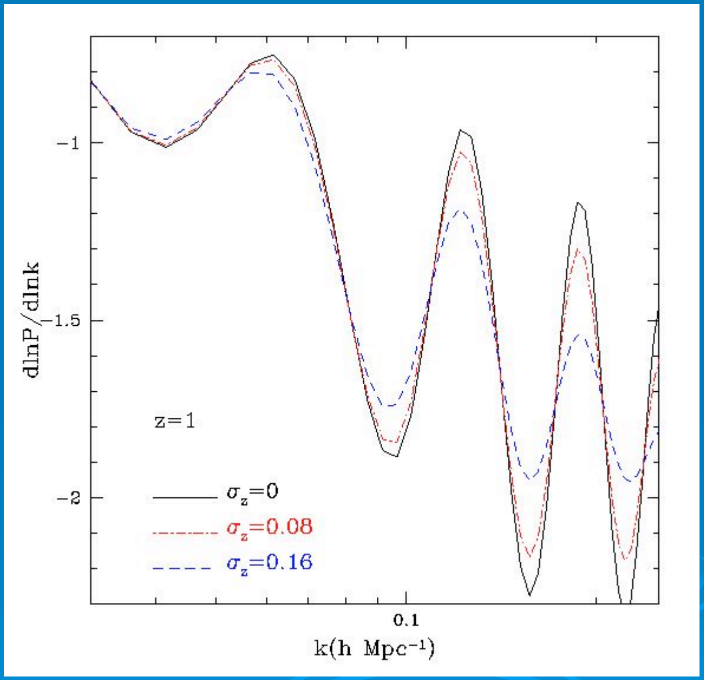
Spergel

Conclusions

- Acoustic oscillations provide a robust way to measure $H(z)$ and $D_A(z)$.
  - Clean signature in the galaxy power spectrum.
  - Can probe high redshift; can probe $H(z)$ directly.
- SDSS LRG sample uses BAO to measure $D_A(z=0.35)$ to 4%. Larger galaxy surveys will push to 1% in the coming decade.
- SDSS-III will pursue large surveys on 3 major themes. Collaboration forming now.
- SDSS-III highly complementary to WFMOS
  - Build BAO distance scale across redshift.
  - High-res IR & optical investigation of the Milky Way.
  - Continue the momentum of large spectroscopic surveys.

Photometric Redshifts?

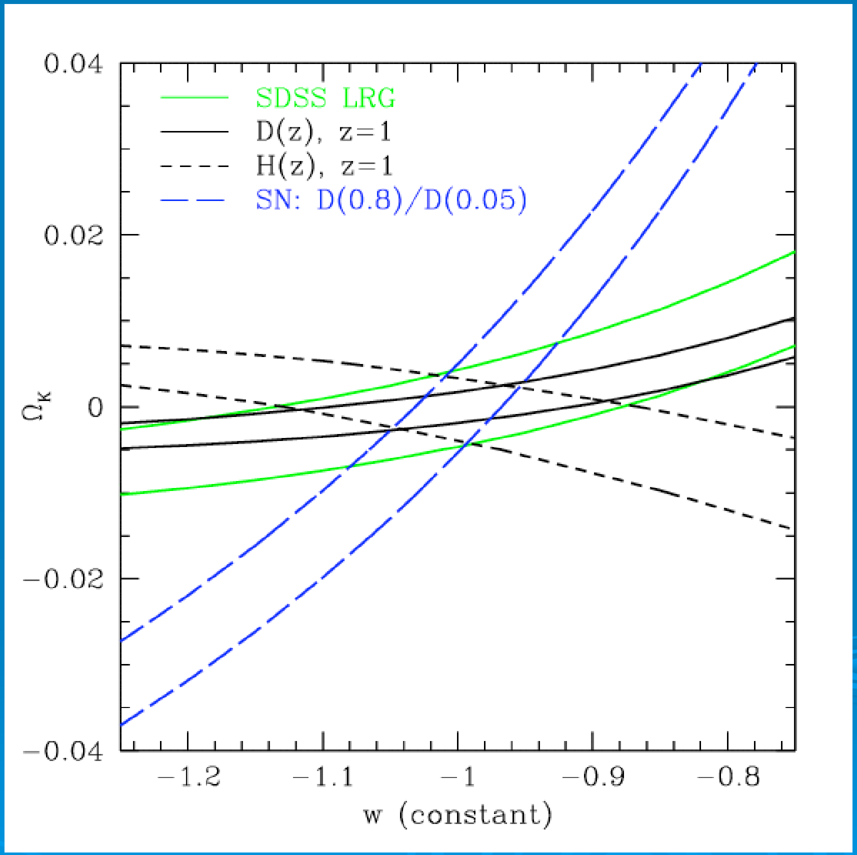
- Can we do this without spectroscopy?
- Measuring H(z) requires detection of acoustic oscillation scale along the line of sight.
  - Need ~10 Mpc accuracy. σ_z~0.003(1+z).
- Measuring $D_A(z)$ from transverse clustering requires only 4% in 1+z.
- Need 10x more sky than spectroscopy. Less robust, but likely feasible.
- First work by Padmanabhan et al (2006) and Blake et al (2006). 6% distance to z = 0.5.



4% photo-z's don't smear the acoustic oscillations.

Breaking the *w*-Curvature Degeneracy

- To prove $w \neq -1$, we should exclude the possibility of a small spatial curvature.
- SNe alone, even with space, do not do this well.
- SNe plus acoustic oscillations do very well, because the acoustic oscillations connect the distance scale to z=1000.

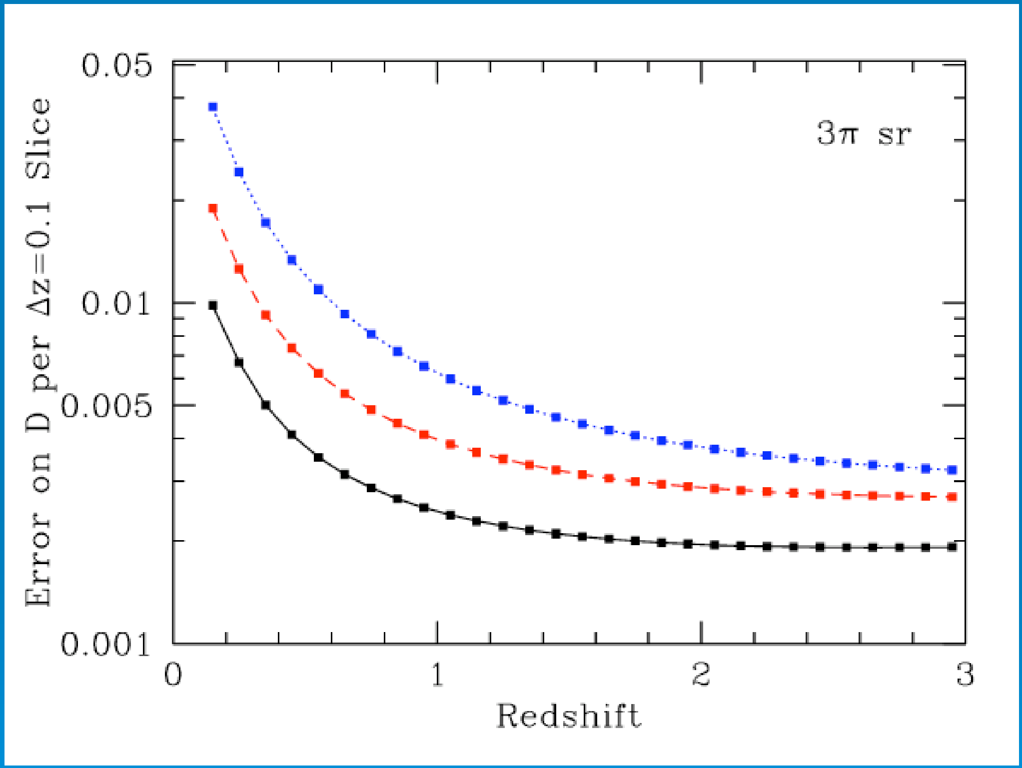


What about H_0?

- Does the CMB+LSS+SNe really measure the Hubble constant? What sets the scale in the model?
  - The energy density of the CMB photons plus the assumed a neutrino background gives the radiation density.
  - The redshift of matter-radiation equality then sets the matter density ($\Omega_m h^2$).
  - Measurements of Ω_m (e.g., from distance ratios) then imply H_0.
- What if the radiation density were different, i.e. more/fewer neutrinos or something new?
  - Sound horizon would shift in scale. LSS inferences of Ω_m, Ω_k, $w(z)$, etc, would be correct, but $\Omega_m h^2$ and H_0 would shift.
  - Minor changes in baryon fraction and CMB anisotropic stress.
- So comparison of H_0 from direct measures to CMB-based inferences are a probe of “dark radiation”.
  - 1 neutrino species is roughly 5% in H_0.
  - We could get to ~1%.

DJE & White (2004)

Cosmic Variance Limits



Seo & DJE, 2007

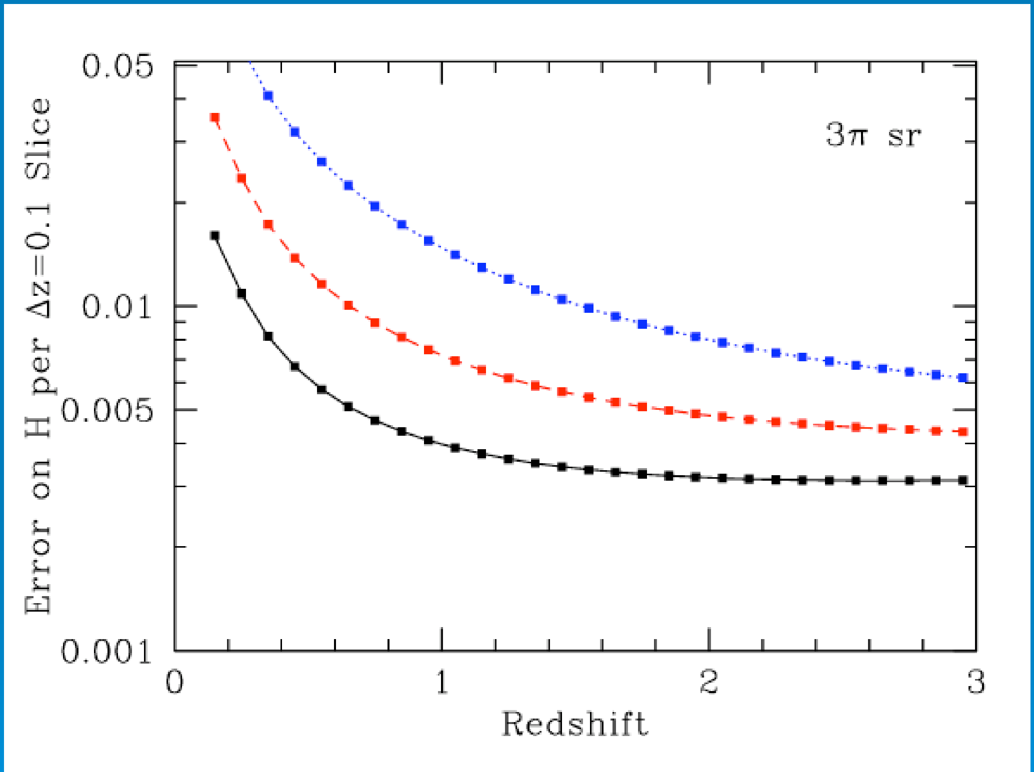
Errors on $D(z)$ in Δz=0.1 bins. Slices add in quadrature.

Black: Linear theory

Blue: Non-linear theory

Red: Reconstruction by 50% (reasonably easy)

Cosmic Variance Limits



Seo & DJE, 2007

Errors on $H(z)$ in Δz=0.1 bins.
Slices add in quadrature.

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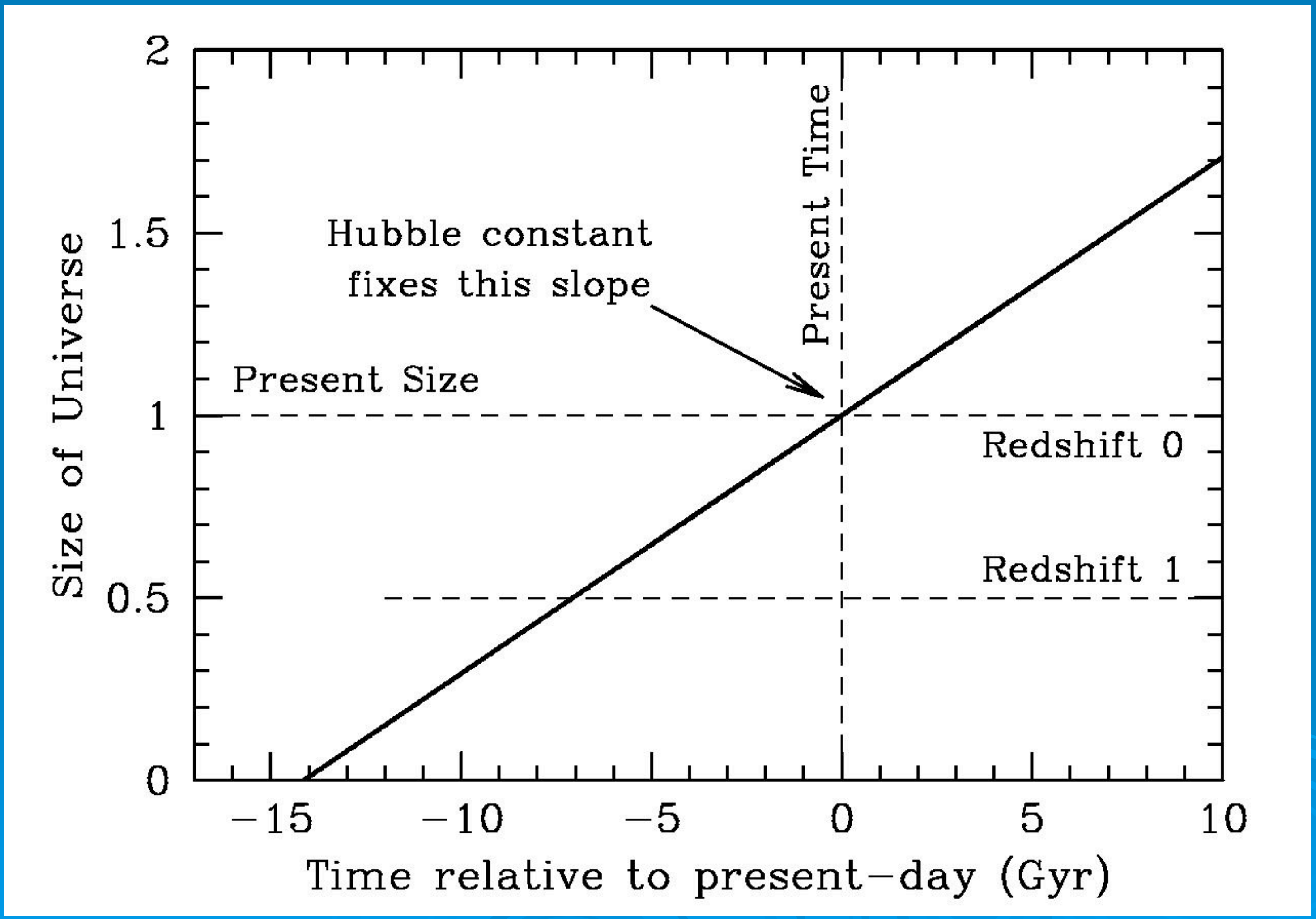
DETF Figure of Merit

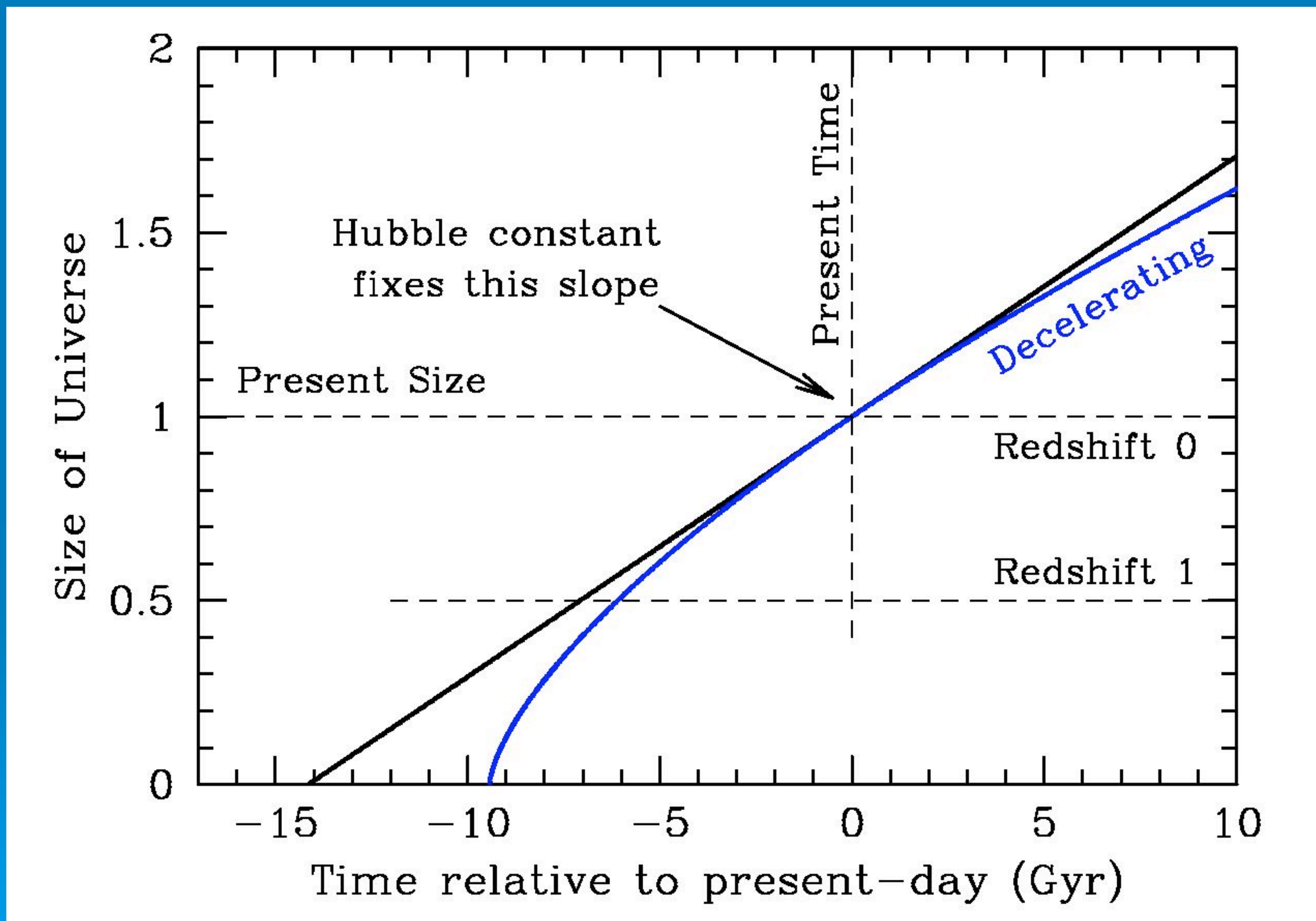
Experiment	DETF FOM
Stage II + Planck	67
+ BOSS LRG BAO	97
+ BOSS QSO BAO	144
+ BOSS Galaxy power spectrum	270

- Powerful Stage III data set.
- High complementarity with future weak lensing and supernova data sets.

Distances to Acceleration



Distances to Acceleration



Distances to Acceleration