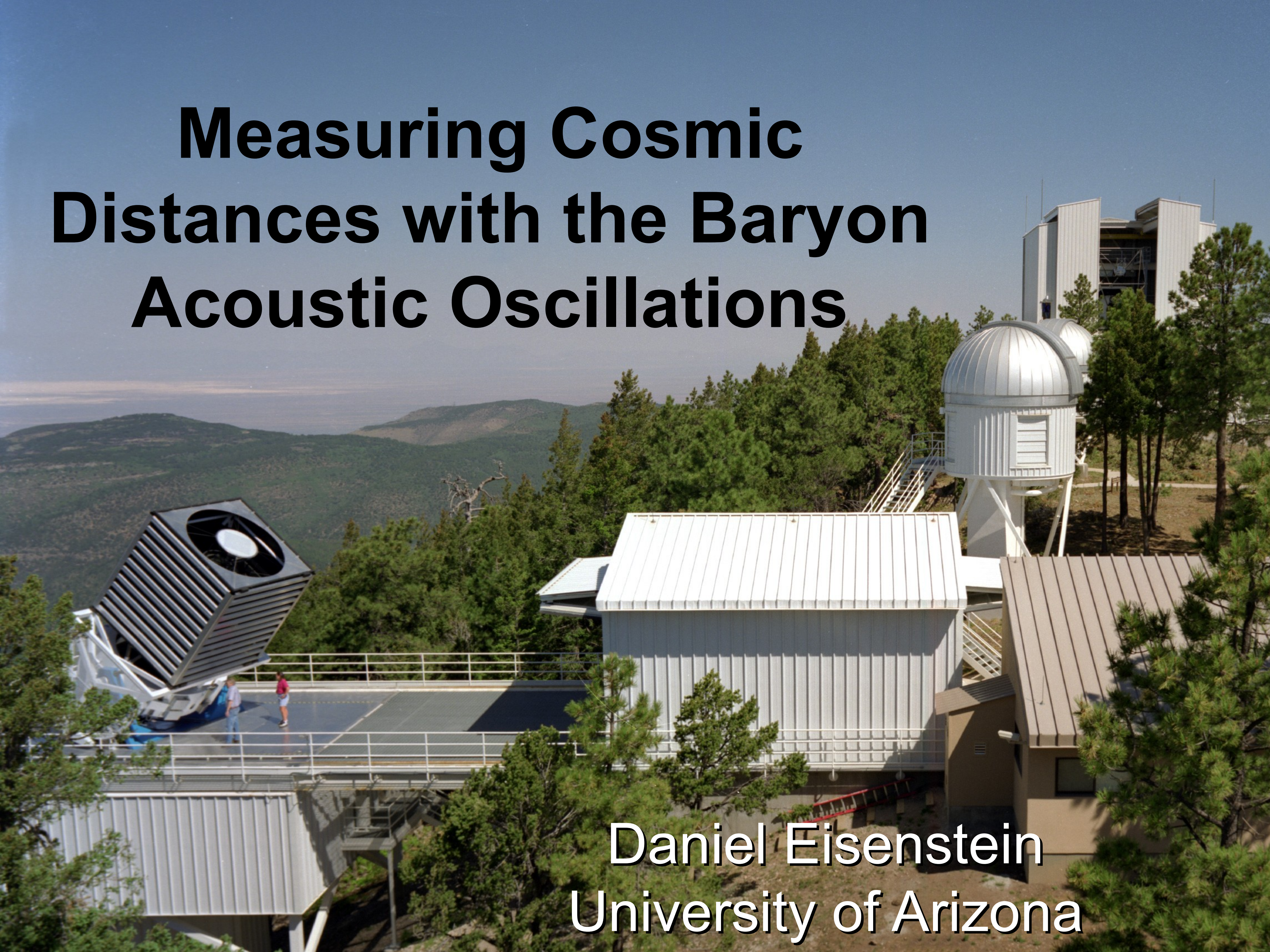
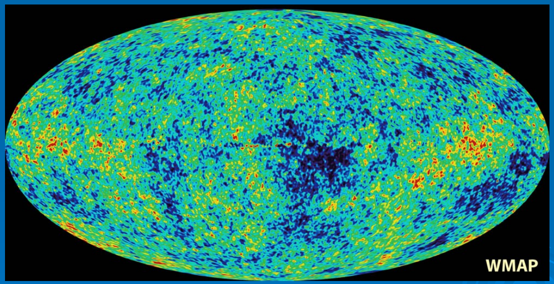
Measuring Cosmic Distances with the Baryon Acoustic Oscillations

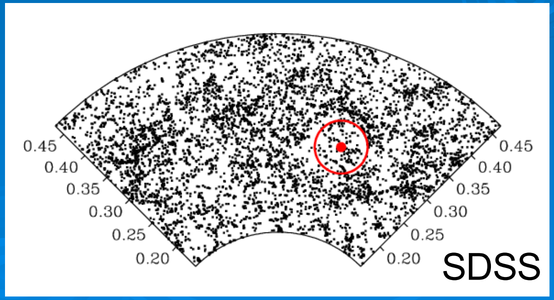


Daniel Eisenstein
University of Arizona

SDSS & Large-Scale Structure

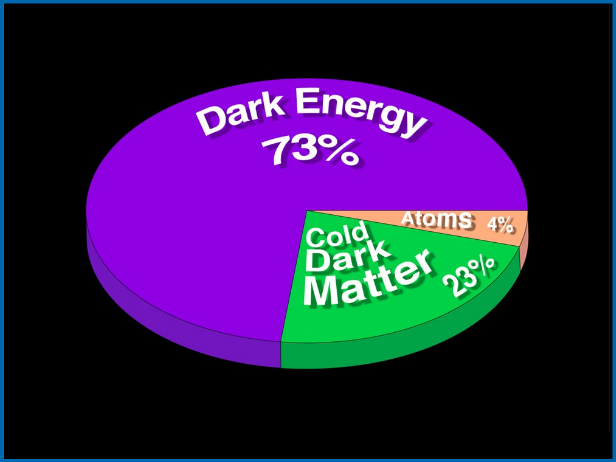
- The clustering of matter on large scales has two different roles in modern cosmology.
  - Provides a window into the early Universe, probing the composition and forces as a function of time.
  - Provides the underlying scene for the formation of galaxies, clusters, and other luminous structures. A recasting of the role of environment.
- The theory of large-scale structure unites many different observations:
  - Cosmic microwave background anisotropies
  - Galaxy clustering & clusters of galaxies
  - Lyman α forest & other IGM tracers
  - Weak lensing
  - Galaxy formation and evolution

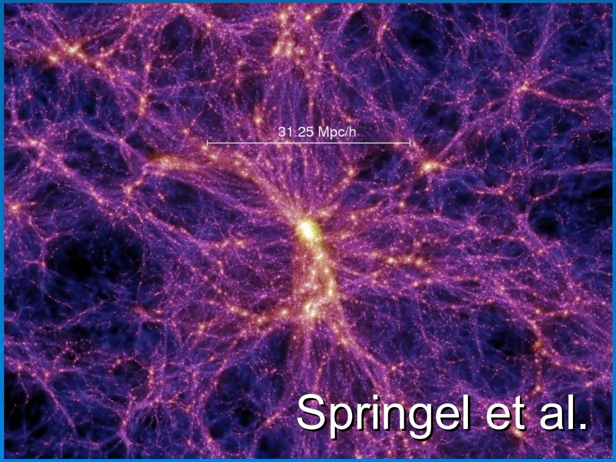




Clustering Regimes

- Cosmological perturbations begin small but grow over time. When they reach order unity, they collapse into halos.
- Large scales (>30 Mpc)
  - Linear perturbation theory, simple outcome of clustering bias.
  - Window into early Universe.
- Small scales (<few Mpc) and quasi-linear scales (3-30 Mpc)
  - Non-linear gravity, increasingly complicated segregation of light and mass.
  - Scene for galaxy formation.





Springel et al.

Cosmic Concordance

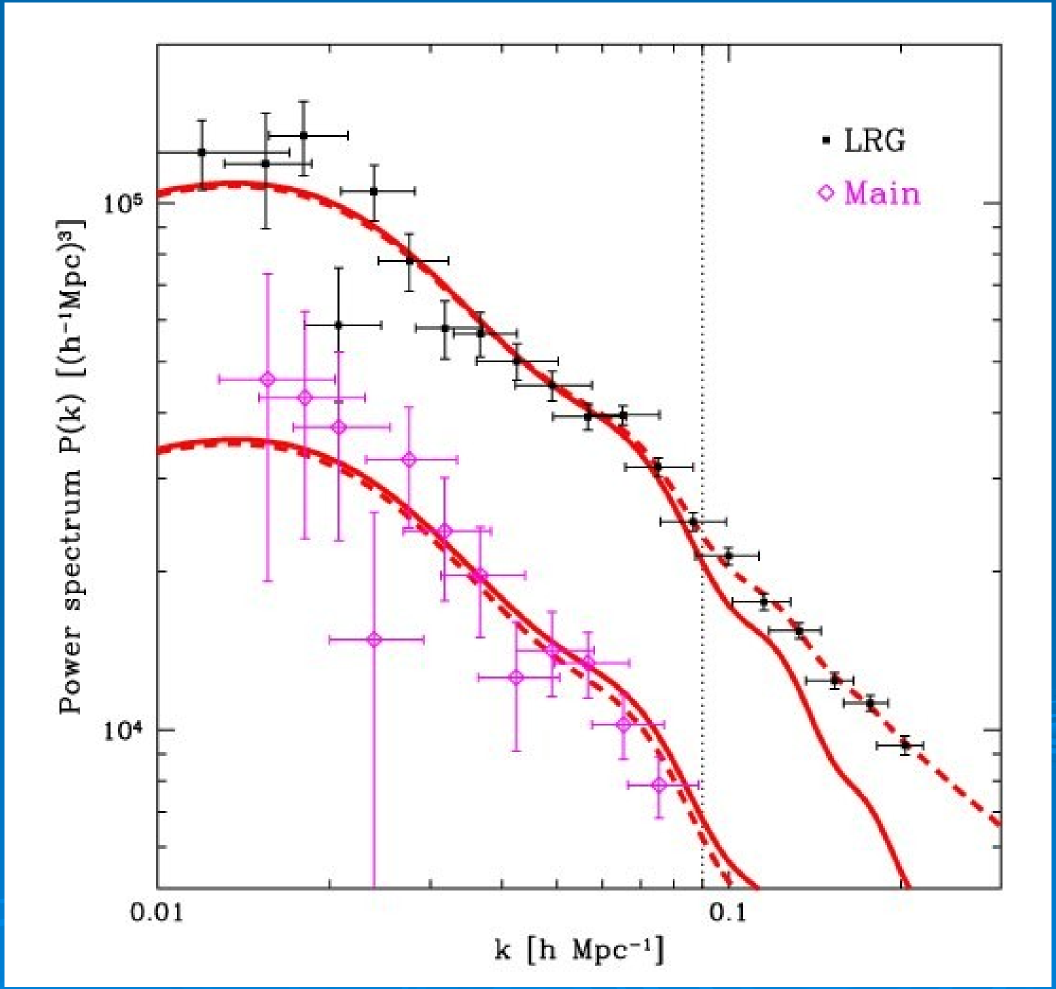
- Last decade of observations has been a stunning success in cosmology.
  - CMB Anisotropies
  - LSS from SDSS & 2dF
  - Discovery of dark energy with SNe
  - Predictive model matches many observations across wide range of scales from 1 second after the Big Bang until today.
- Standard cosmological model now established and offers opportunity to pursue precision measurements.
  - Dark Energy: cosmological constant or not? If not, what?
  - Dark Matter, deviations from CDM
  - Primordial spectrum
  - Primordial non-Gaussianity
  - Isocurvature admixtures
  - Neutrino Masses
  - Gravitational waves from the early Universe
  - Particle decays

Outline

- Galaxy and Lyman α forest power spectra.
- 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.

SDSS Galaxy Clustering

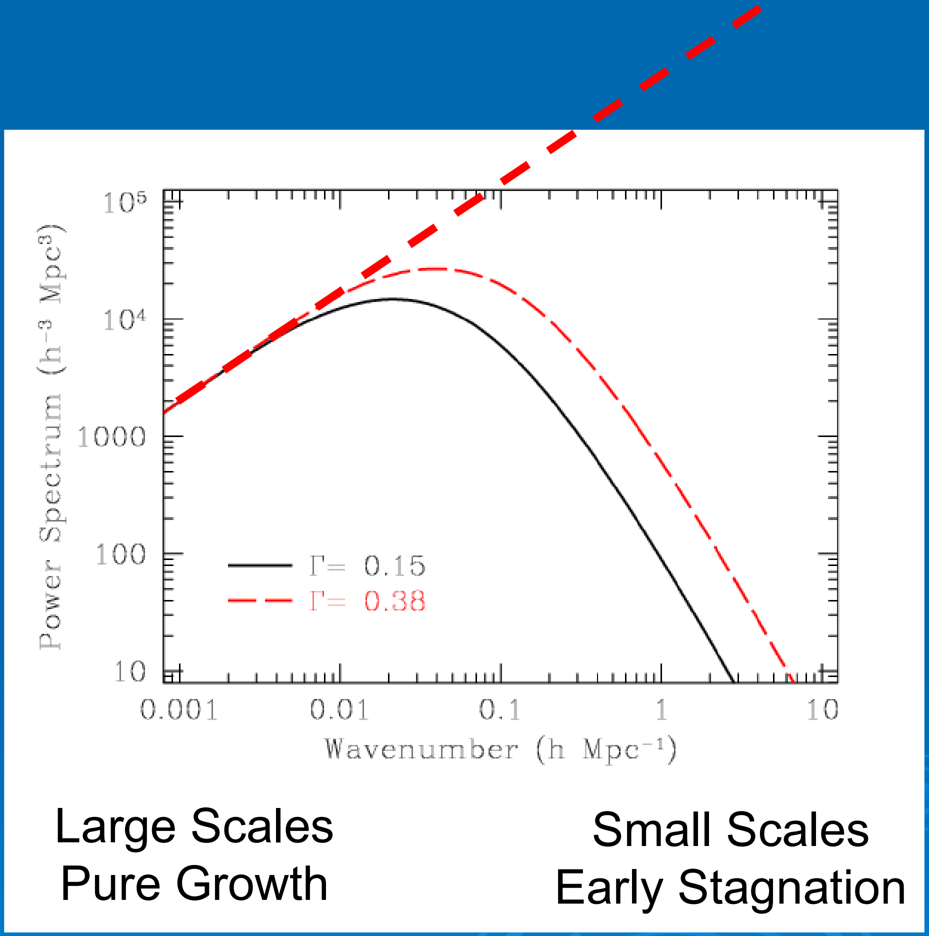
- Power spectrum has been computed in several different ways and different teams within the project.
- Marvelous match to adiabatic CDM model.



Tegmark et al. (2006)

Matter-Radiation Equality

- CDM theories predict a deficit of small-scale power, due to the lack of growth of sub-horizon perturbations during the radiation-dominated era.
- Turnover depends on scale of horizon at matter-radiation equality and hence on the amount of mattter.
- More matter means more small-scale growth, or less large-scale power relative to small-scale.



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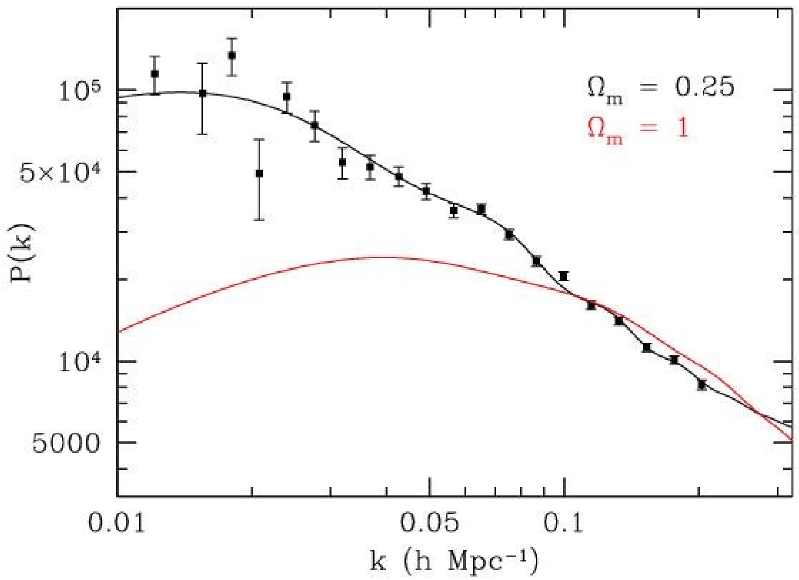


High n_m models produce insufficient large-scale power

Data from Tegmark et al. (2006)

Lyman α Forest Cosmology

- Absorption by neutral hydrogen along the line of sight to high-z quasars traces the intergalactic density field.
- Measure the amplitude and spectral slope of clustering on small scales (k~1*h* Mpc^{-1}).
  - Still essentially in the linear regime.
- The extra lever arm sharply improves the constraints on cosmological parameters.

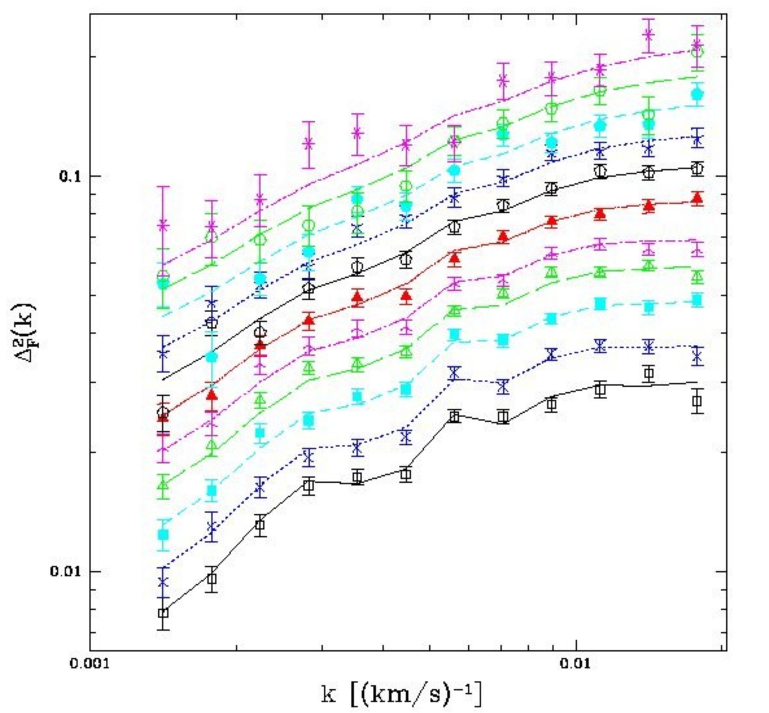


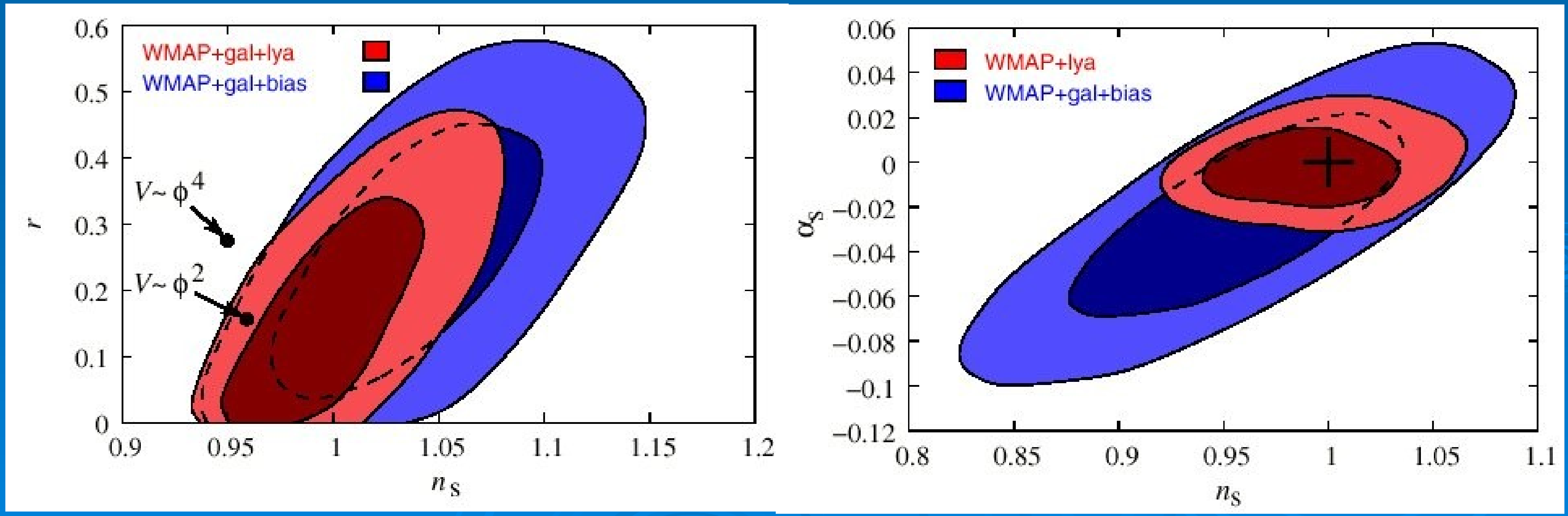
Fig. 14.— Points with error bars show the observed $P_F(k,z)$ from SDSS. Lines show our best fitting model. From bottom to top — z=2.2: black, solid line, open square; z=2.4: blue, dotted line, 4-point star (cross); z=2.6: cyan, dashed line, filled square; z=2.8: green, long-dashed line, open triangle; z=3.0: magenta, dot-dashed line, 3-point star; z=3.2: red, dot-long-dashed line, filled triangle; z=3.4: black, thin solid line, open pentagon; z=3.6: blue, thin dotted line, 5-point star; z=3.8: cyan, thin dashed line, filled pentagon; z=4.0: green, thin long-dashed line, open hexagon; z=4.2: magenta, thin dot-dashed line, 6-point star. Note that the wiggles in the theory curve are caused by SiIII-Lyα cross-correlation.

4.6 Redshift 2.2

McDonald et al. (2004)

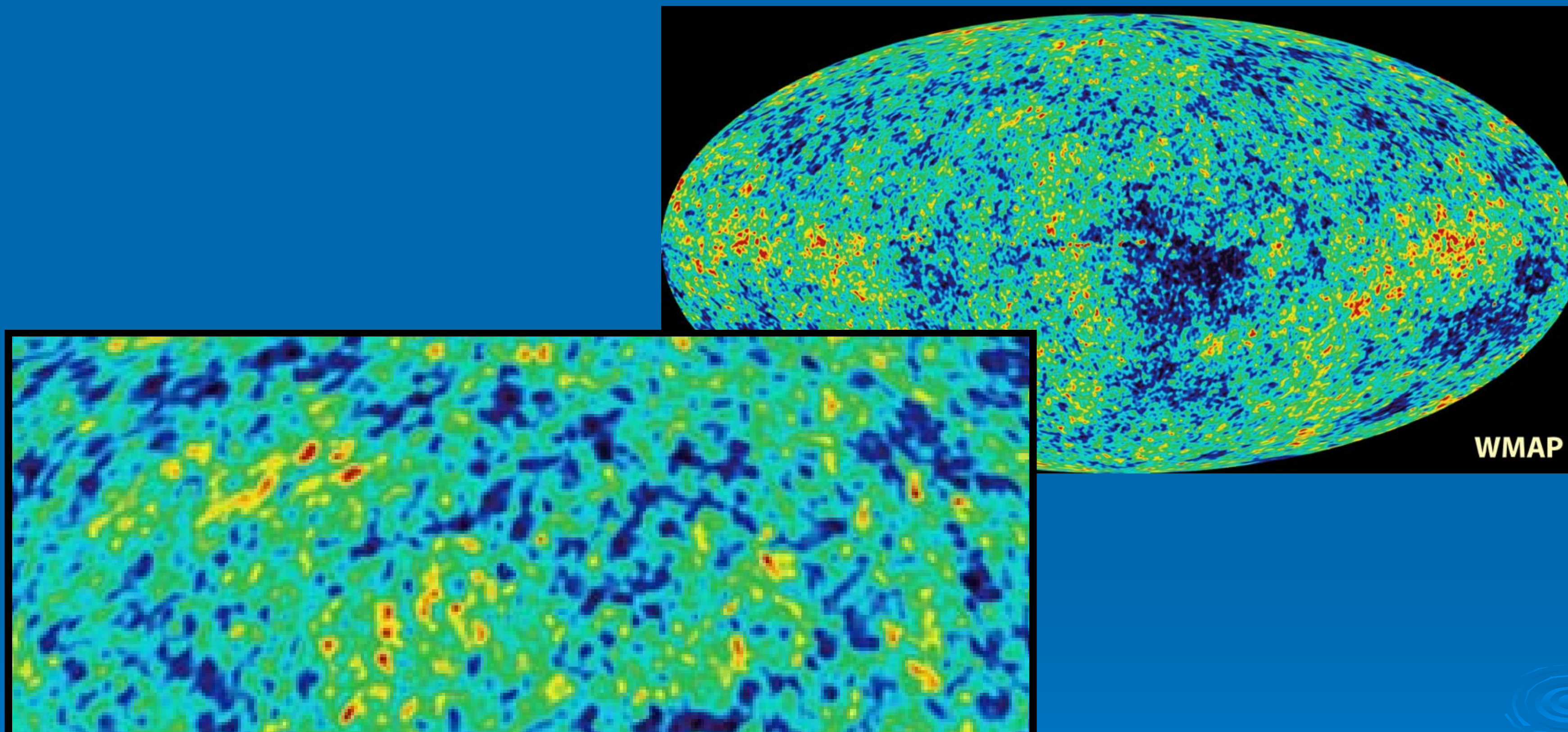
Constraints on Inflation

- Accuracy on “normal” parameters reaching point that we can search for relics of inflation.
  - Gravitational waves
  - Running of spectral tilt



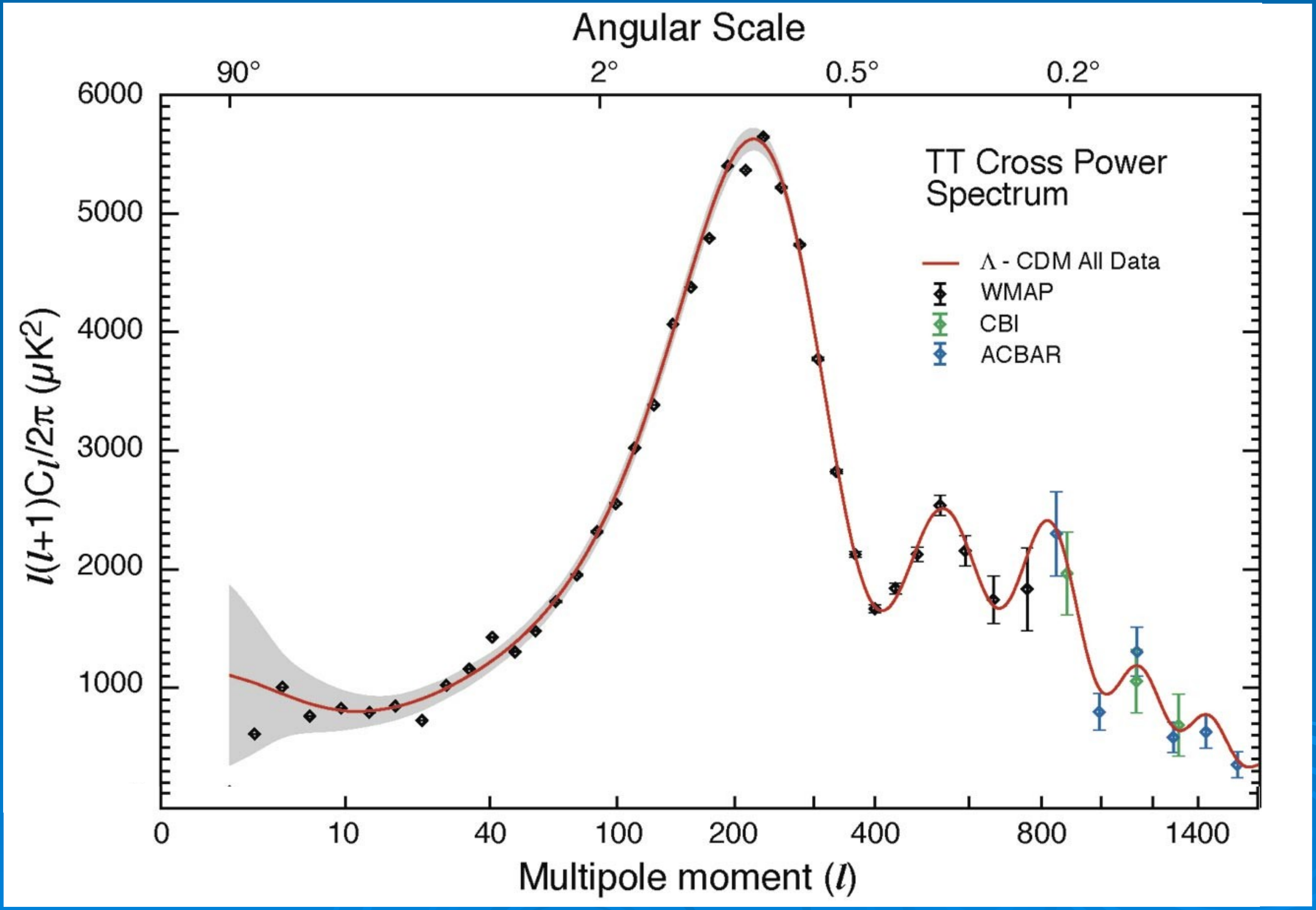
Seljak et al. (2004)

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.

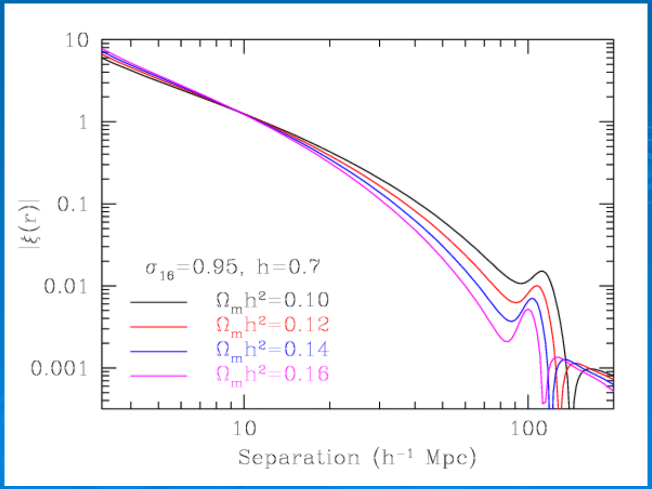
After recombination:

- 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.

QuickTime and a
GIF decompressor
are needed to see this picture.



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.

QuickTime and a
GIF decompressor
are needed to see this picture.

Response of a point perturbation

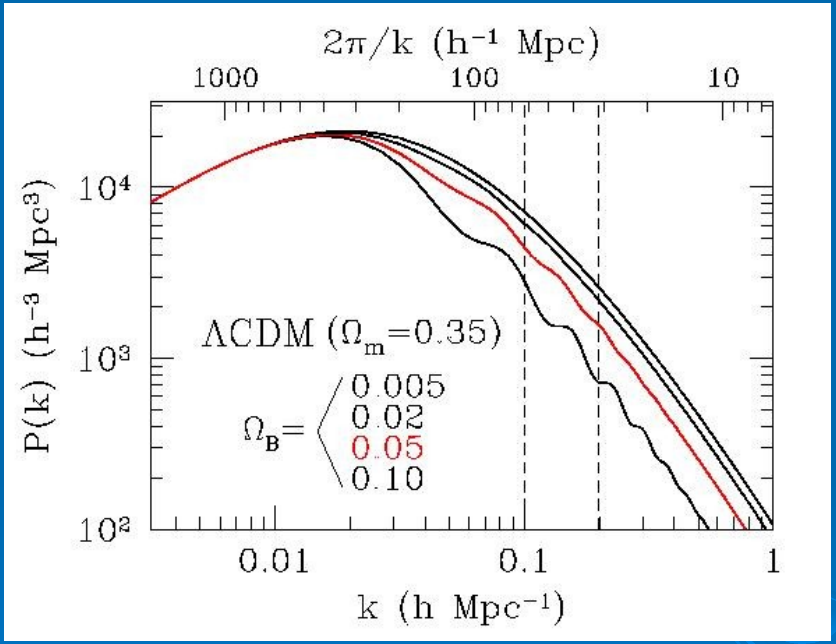
QuickTime and a
GIF decompressor
are needed to see this picture.

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

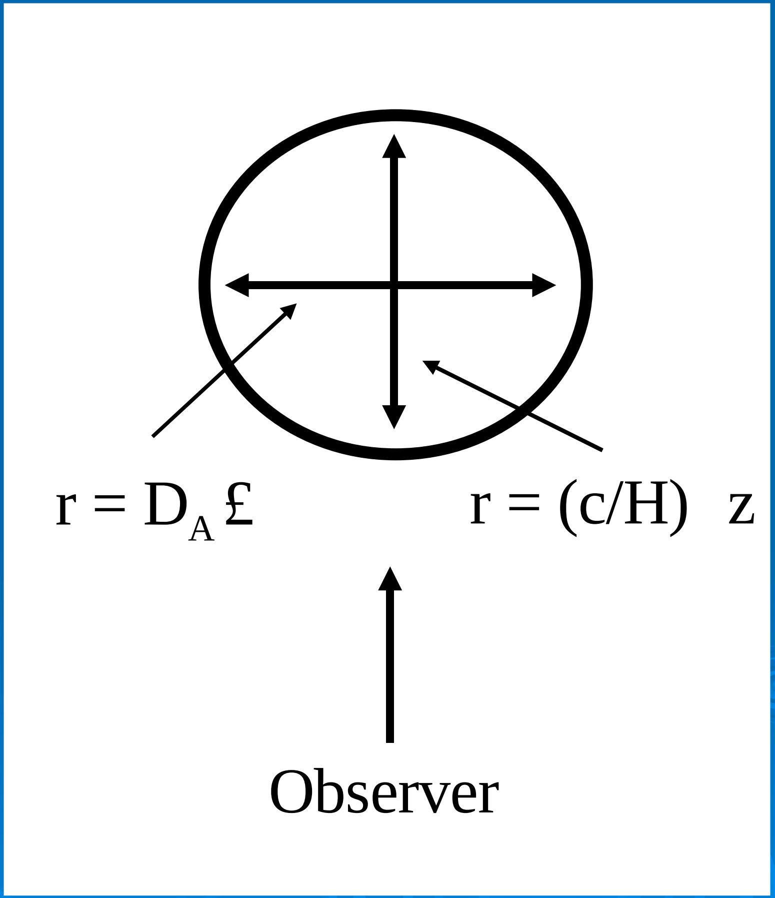
- A crest launches a planar sound wave, which at recombination may or may not be in phase with the next crest.
- Get a sequence of constructive and destructive interferences as a function of wavenumber.
- Peaks are weak — suppressed by the baryon fraction.
- Higher harmonics suffer from Silk damping.



Linear regime matter power spectrum

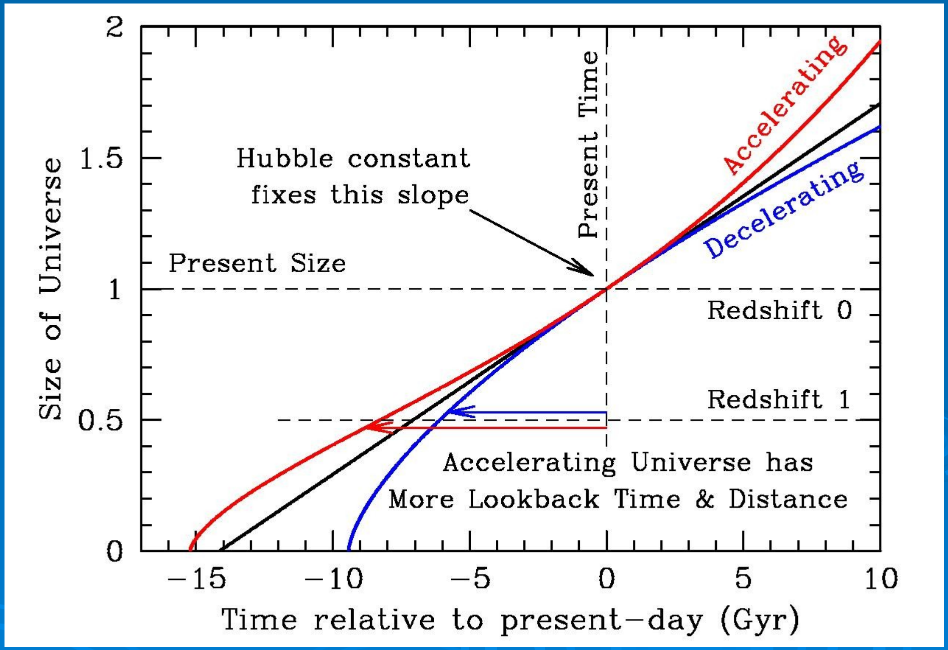
A Standard Ruler

- 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 $D_A(z)$!



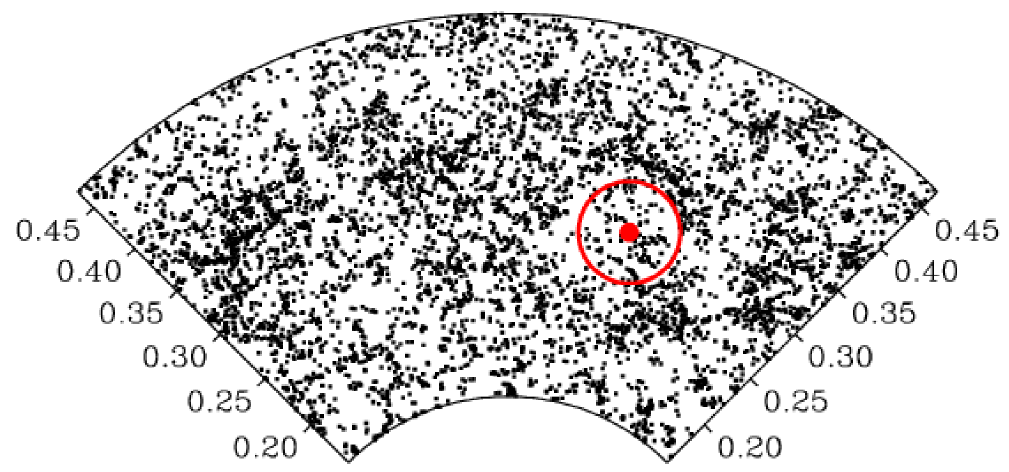
Distances to Acceleration

- Cosmological distance measurements are the entrance to a deep mystery: the acceleration of the expansion rate of the Universe.
  - Cosmological constant?
  - A new force of nature?
  - Modification of gravity?
  - Signature of quantum gravity or extra dimensions?
- The acoustic oscillation method is now a major part of our plans for the study of the dark energy.



Galaxy Redshift Surveys

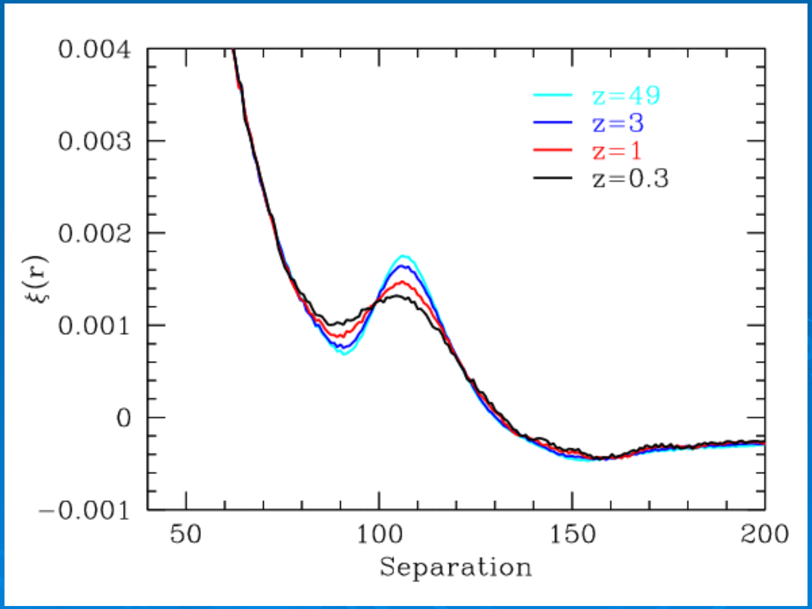
- Redshift surveys are a popular way to measure the 3-dimensional clustering of matter.
- But there are complications from:
  - Non-linear structure formation
  - Bias (light ≠ mass)
  - Redshift distortions
- Partially degrade the BAO peak, but systematics are small because this is a very large preferred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



SDSS

Nonlinear Structure Formaton and the BAO

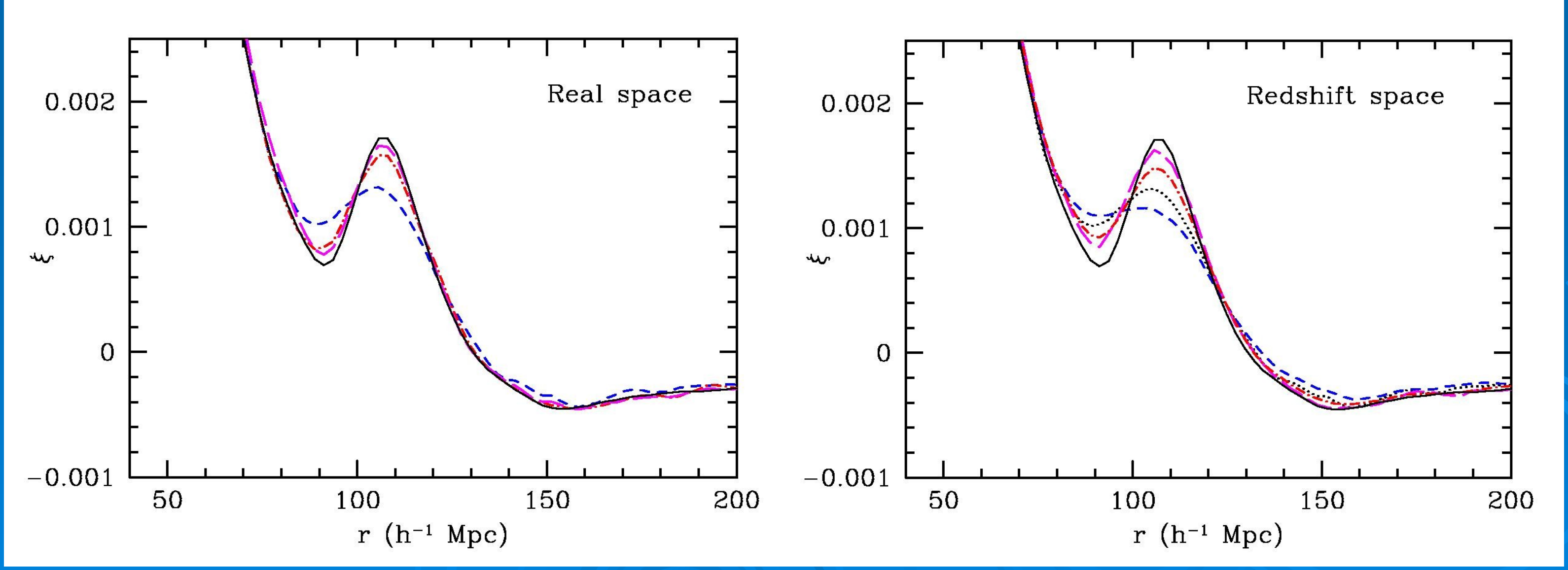
- The acoustic signature is carried by pairs of galaxies separated by 150 Mpc.
- Nonlinearities push galaxies around by 3-10 Mpc. Broadens peak, making it hard to measure the scale.
- Non-linearities are increasingly negligible at z>1. Linear theory peak width dominates.



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

Fixing the Nonlinearities

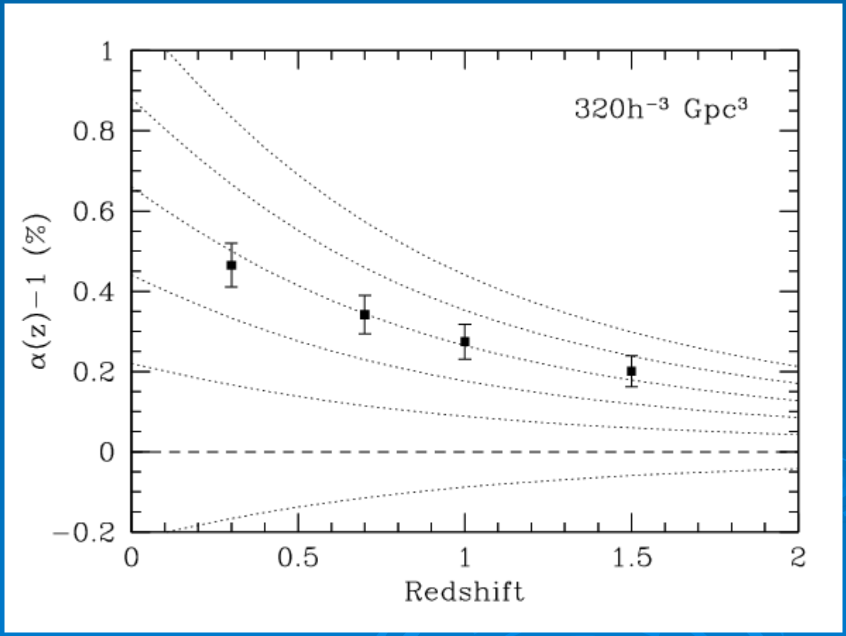
- Most of the non-linear degradation is due to bulk flows. These are produced by the same large-scale structure that we are measuring for the BAO signature.
- Map of galaxies tells us where the mass is that sources the gravitational forces that create the bulk flows.
- Can run this backwards and undo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



DJE, Seo, Sirko, & Spergel (2007)

Shifting the Acoustic Scale

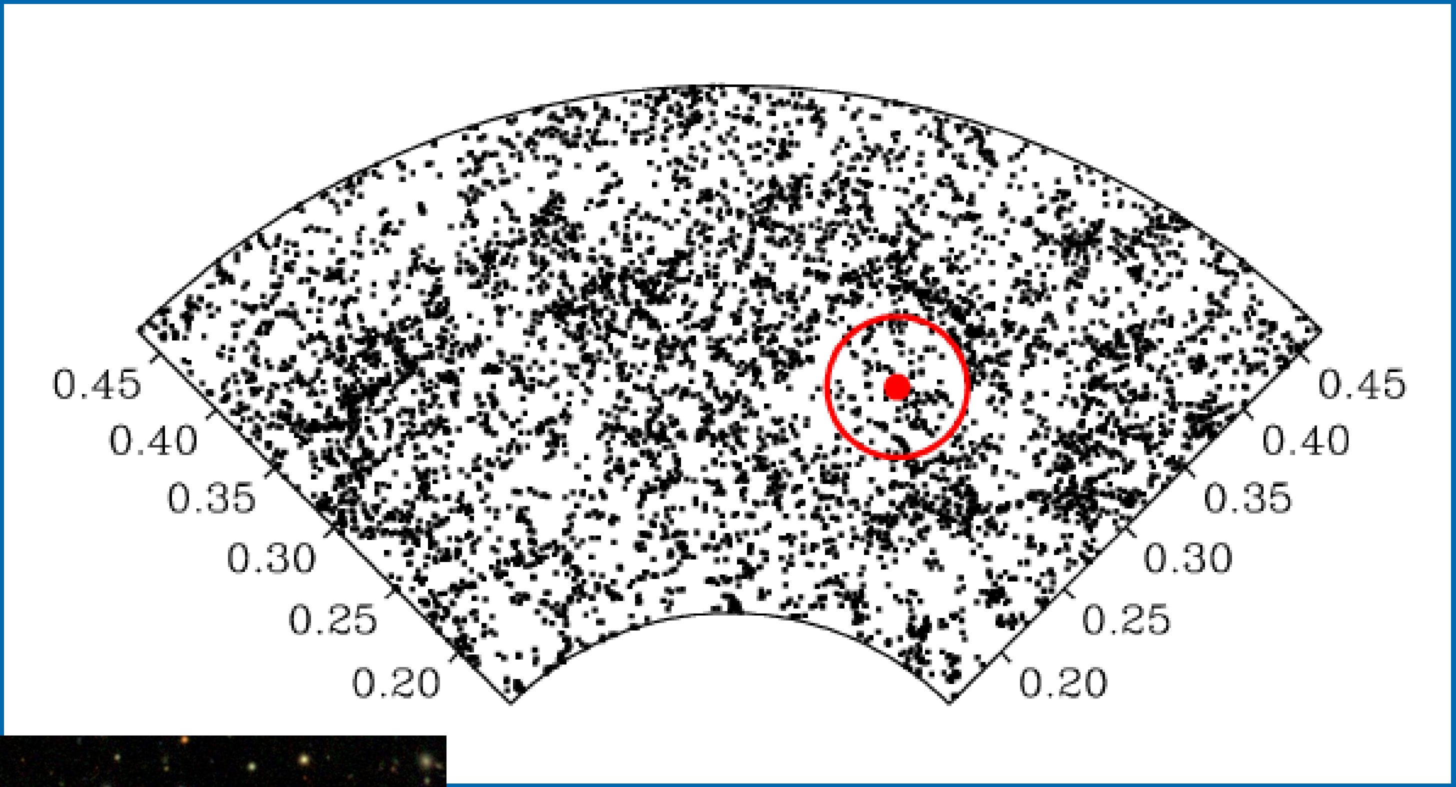
- Moving the acoustic scale requires net infall on 100 h^{-1} Mpc scales. Much smaller than random motions on small-scales. Expect infalls are <1%.
- We have used $320h^{-3}$ Gpc^3 of PM simulations to compute the non-linear shifts.
- Find shifts of 0.25% at z=1.5 to 0.5% at z=0.3.
- These shifts are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

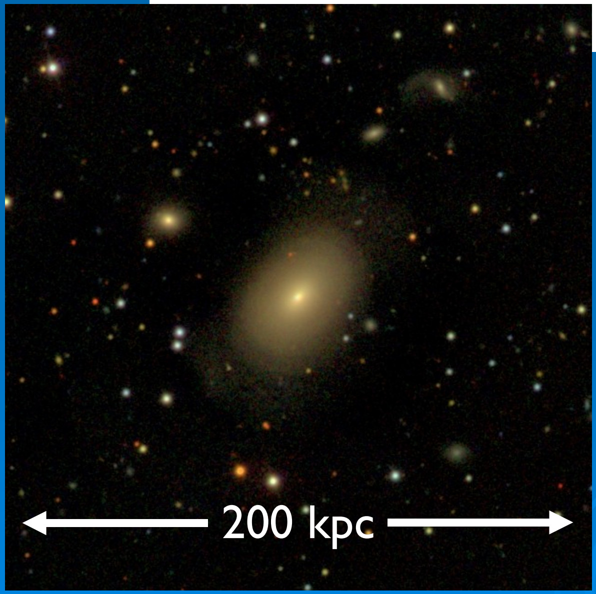


Seo, Siegel, DJE, & White (2008)

Virtues of the Acoustic Peaks

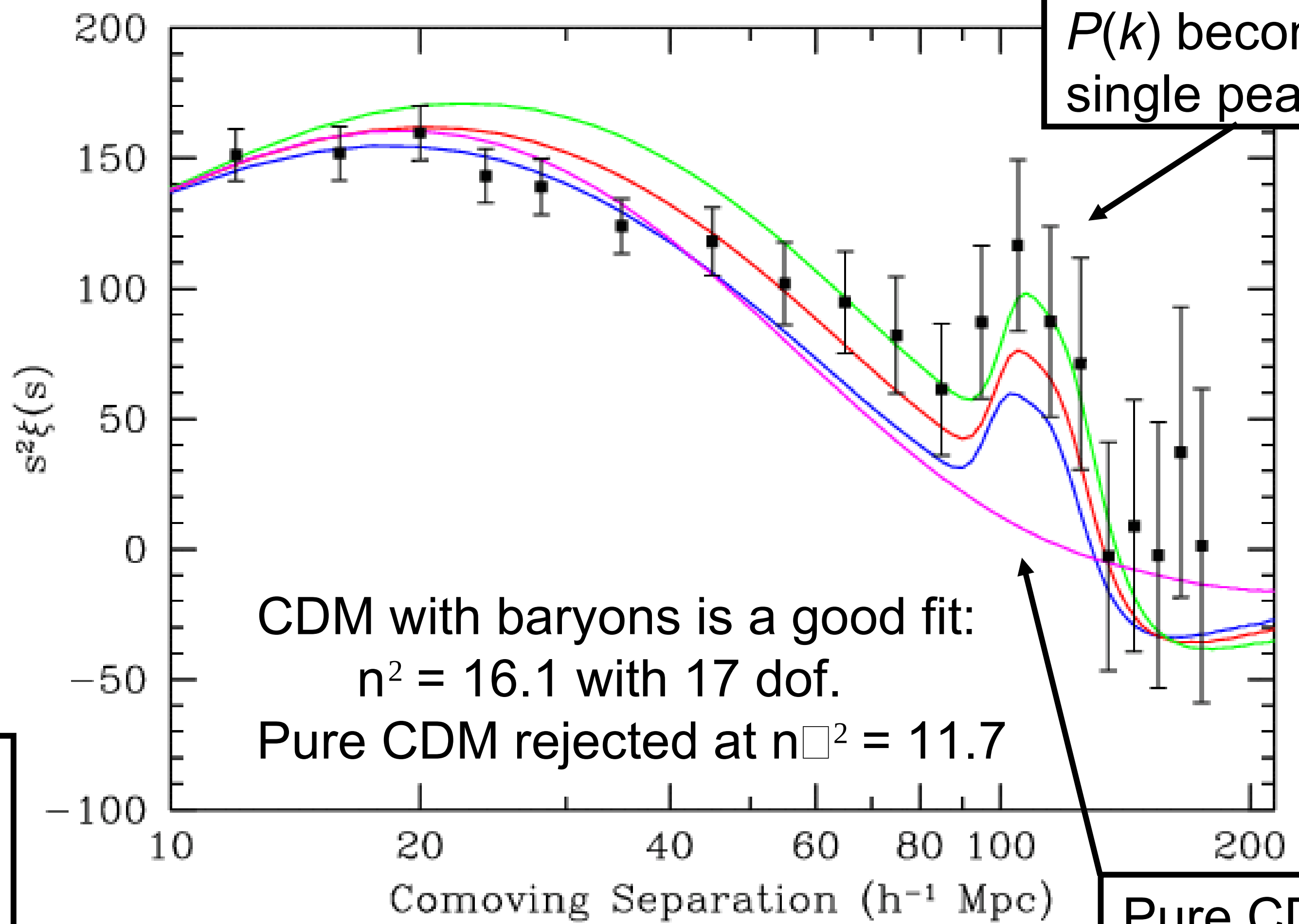
- The acoustic signature is created by physics at z=1000 when the perturbations are 1 in 10^4. Linear perturbation theory is excellent.
- Measuring the acoustic peaks across redshift gives a geometrical measurement of cosmological distance.
- The acoustic peaks are a manifestation of a preferred scale. 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



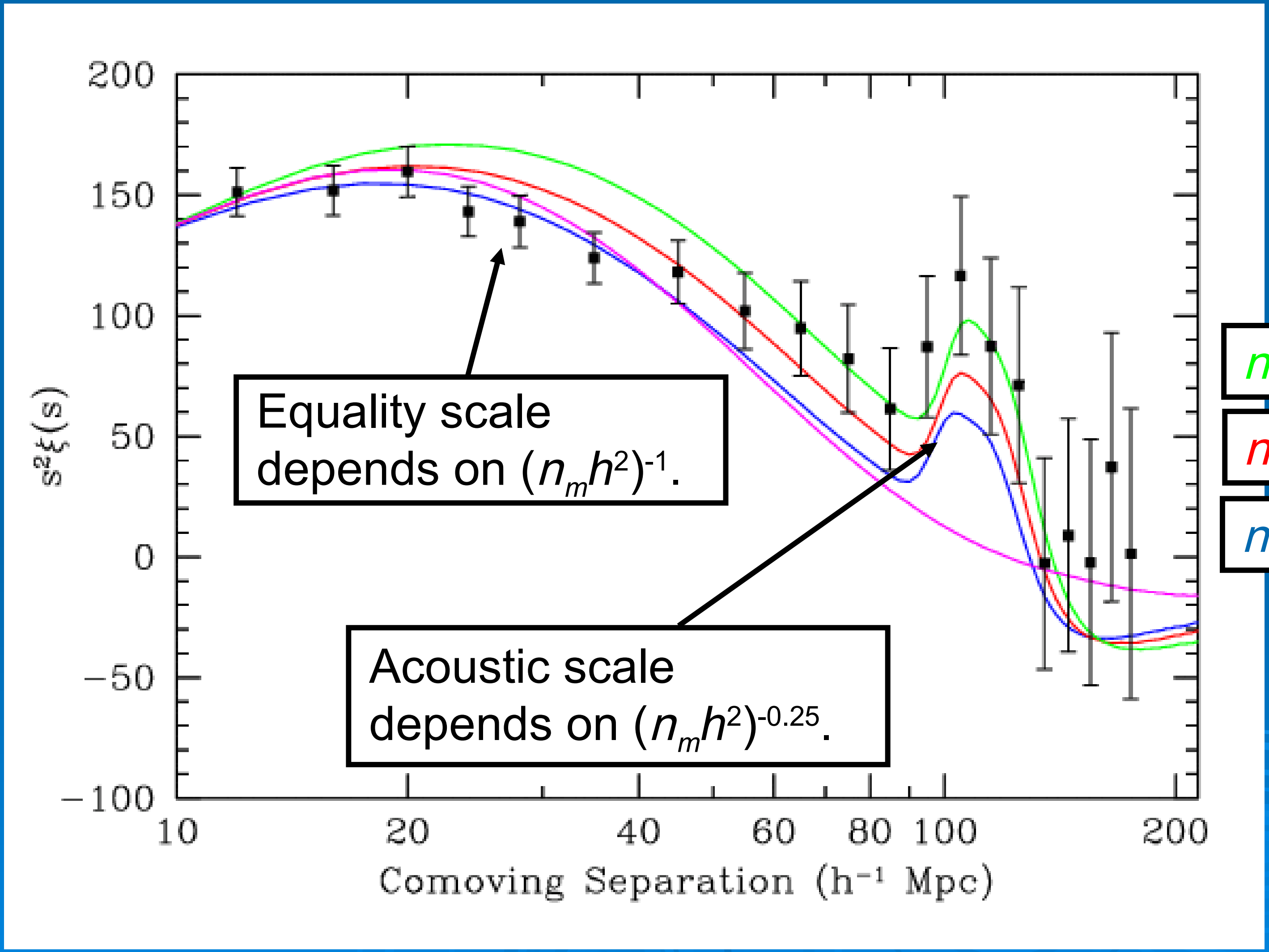
Acoustic series in *P*(*k*) becomes a single peak in *n*(*r*)!

CDM with baryons is a good fit:
n^2 = 16.1 with 17 dof.
Pure CDM rejected at n□^{2} = 11.7

Warning: Correlated Error Bars

Pure CDM model has no peak.

Using the Standard Ruler

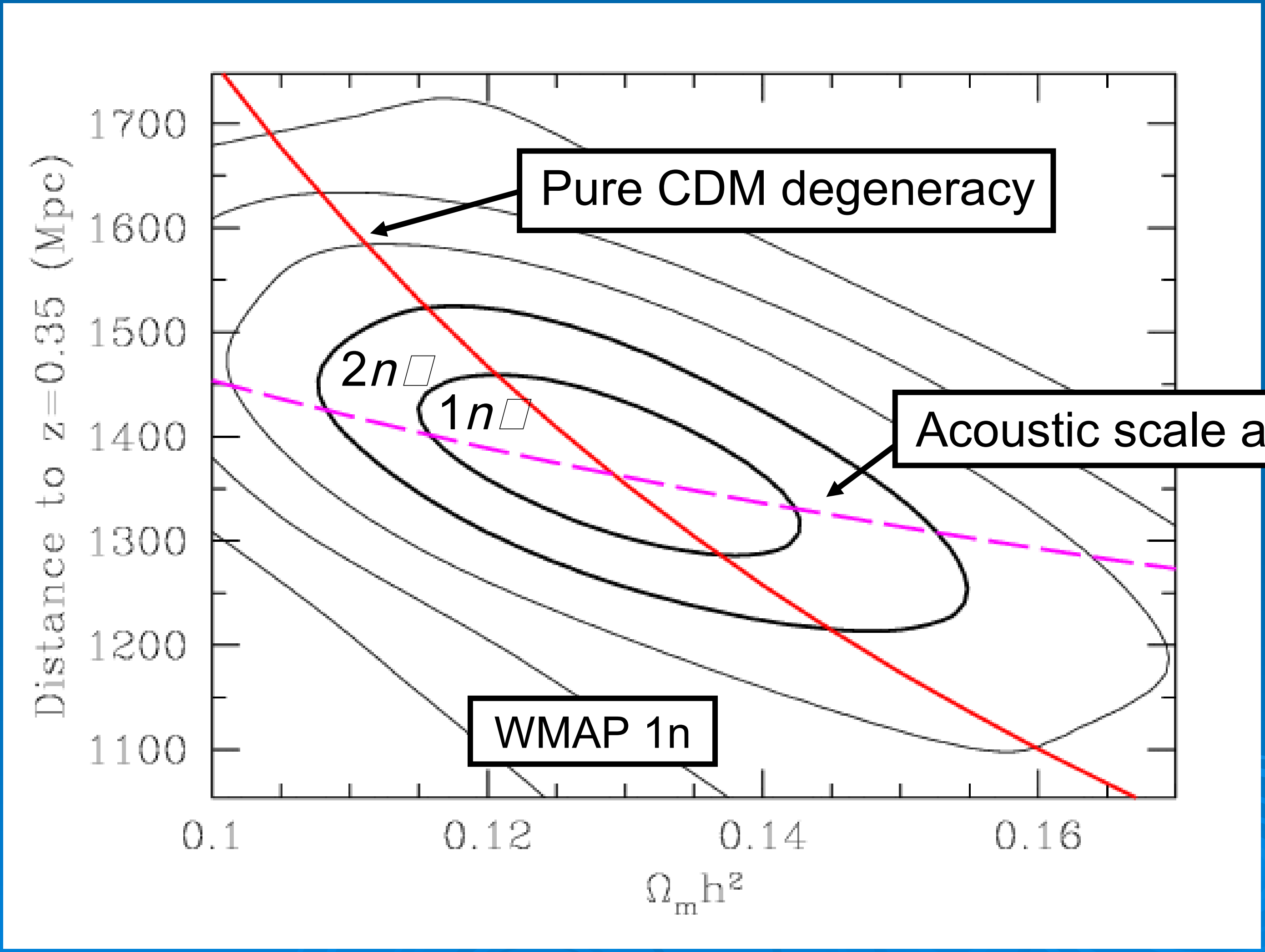


$n_m h^2 = 0.12$

$n_m h^2 = 0.13$

$n_m h^2 = 0.14$

Cosmological Constraints

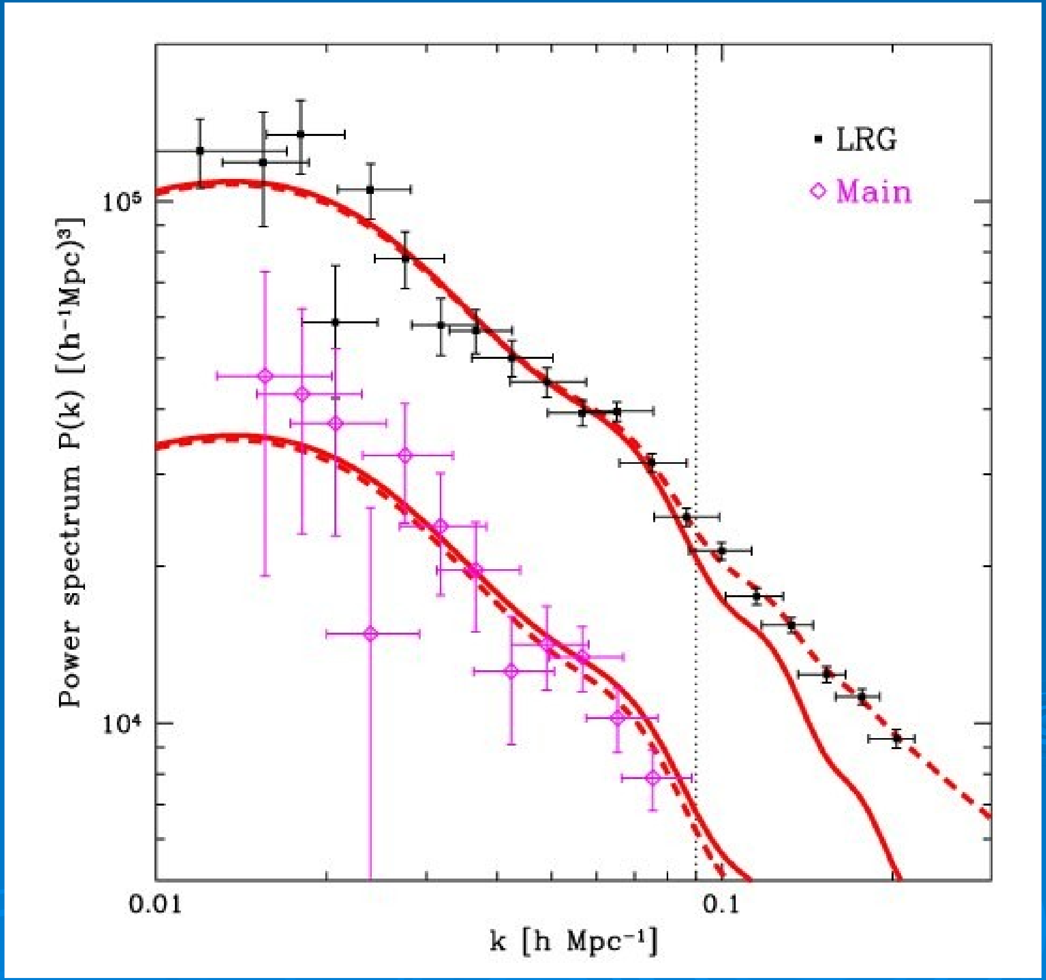


Essential Conclusions

- 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.
- $\Omega_m = 0.273 \pm 0.025 + 0.123(1+w_0) + 0.137\,\Omega_K$.

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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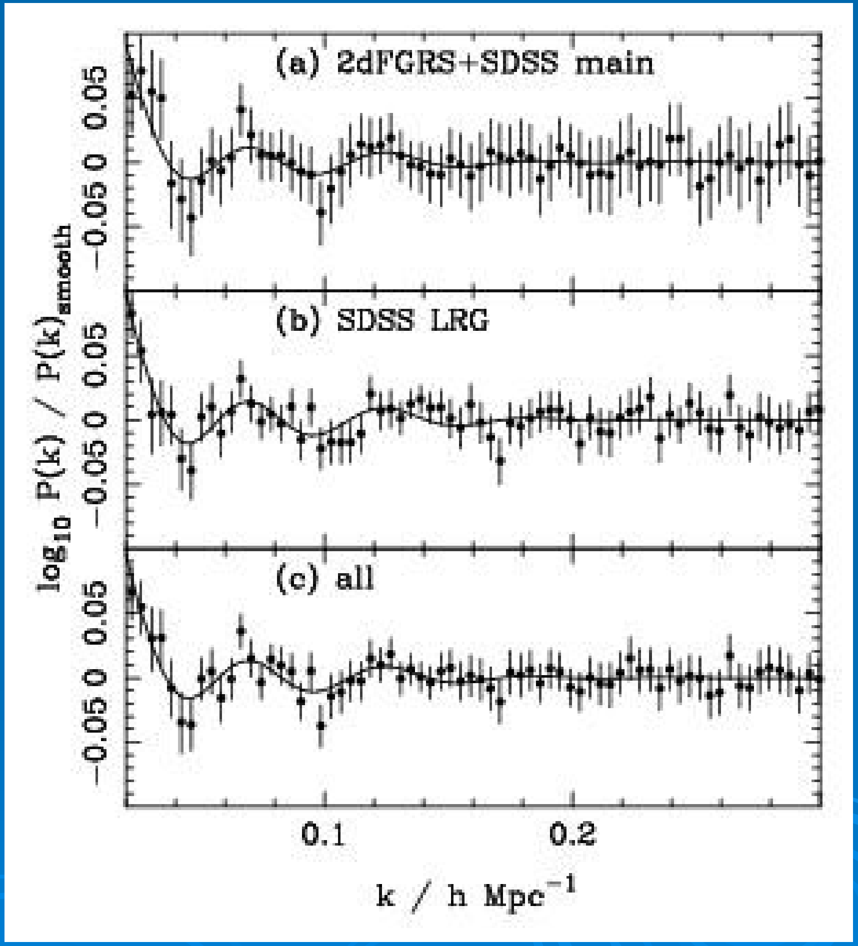


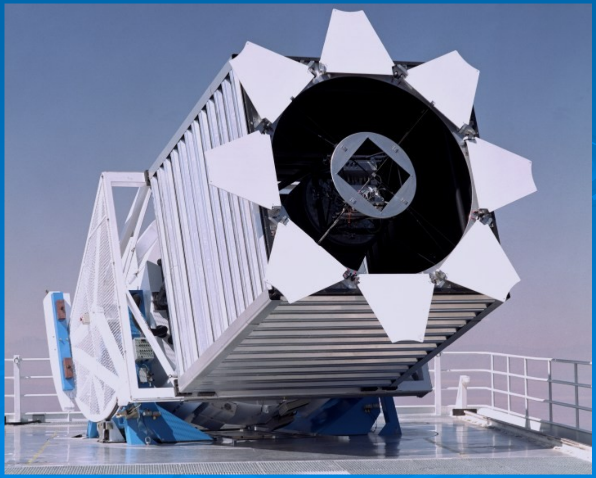
Percival et al. (2007)

SDSS-III

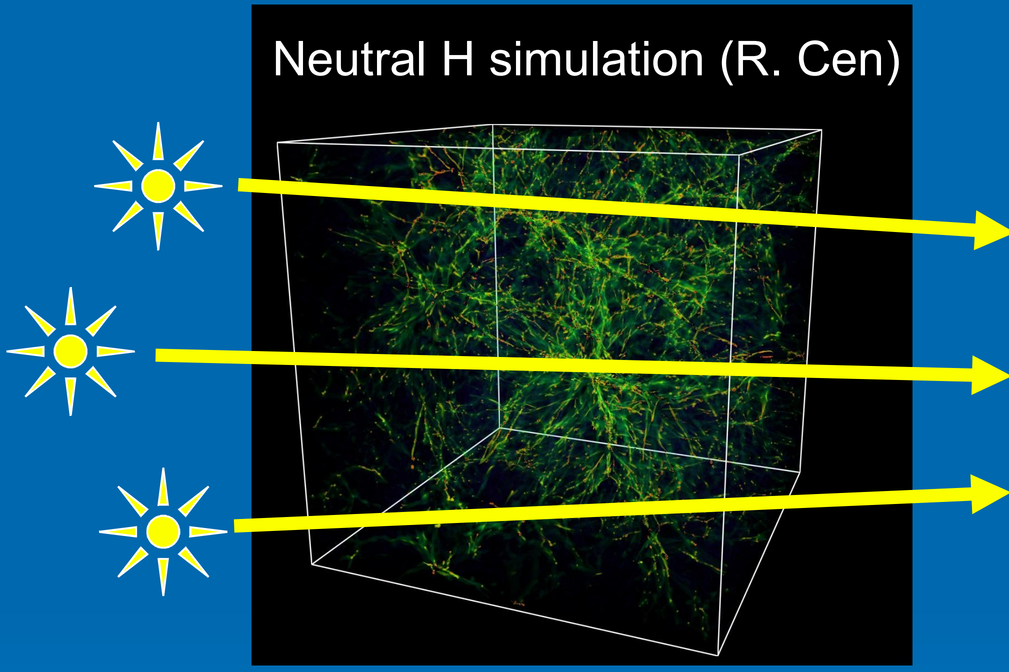
- SDSS-III is the next phase of the SDSS project, operating from summer 2008 to summer 2014.
- SDSS-III has 4 surveys on 3 major themes.
  - BOSS: Largest yet redshift survey for large-scale structure.
  - SEGUE-2: Optical spectroscopic survey of stars, aimed at structure and nucleosynthetic enrichment 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.

Baryon Oscillation Spectroscopic Survey (BOSS)

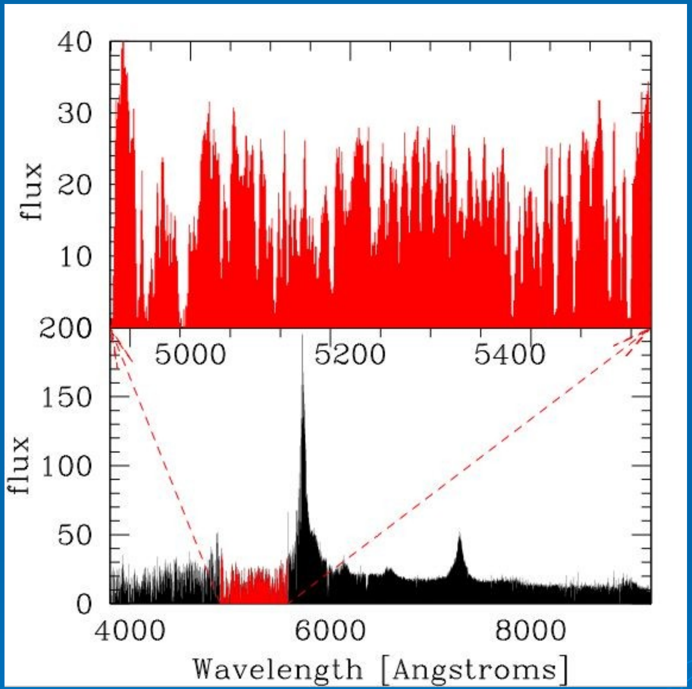
- New program for the SDSS telescope for 2008–2014.
- Definitive study of the low-redshift acoustic oscillations. 10,000 deg^2 of new spectroscopy from SDSS imaging.
  - 1.5 million LRGs to z=0.8, including 4x more density at z<0.5.
  - 7-fold improvement on large-scale structure data from entire SDSS survey; measure the distance scale to 1% at z=0.35 and z=0.6.
  - Straight-forward extension of current program.
- Simultaneous project to discover the BAO in the Lyman n 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.



Seeing Sound in the Lyman α Forest



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)

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.

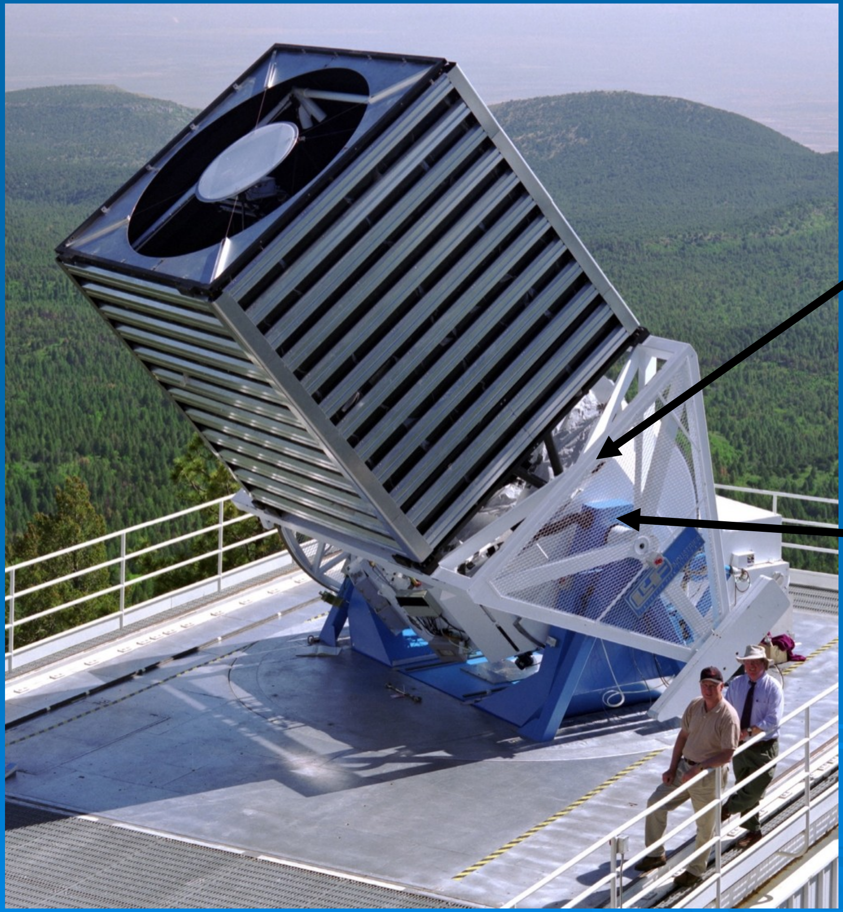
Conclusions

- SDSS has fulfilled its goals as a large-scale structure survey in many ways, some expected, others unexpected.
  - Diverse and compelling support for the standard cosmological model.
- 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%.
- SDSS-III will push to 1% with the definitive study of the low-redshift BAO and will open the study of dark energy at high redshift.

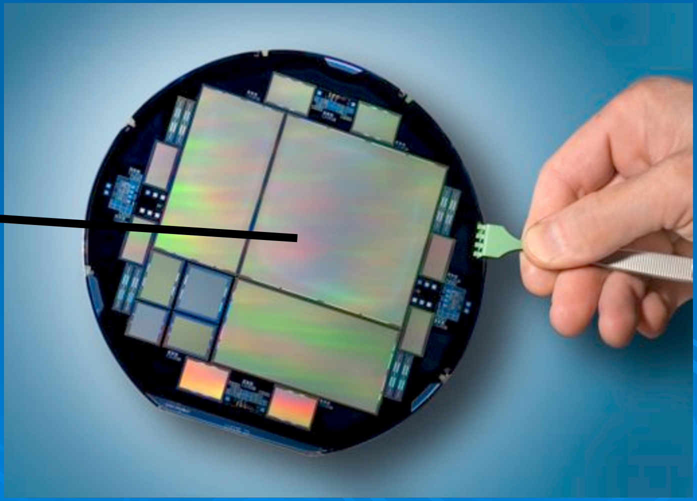
BOSS Instrumentation

" Straightforward upgrades to be commissioned in summer 2009

SDSS telescope + most systems unchanged



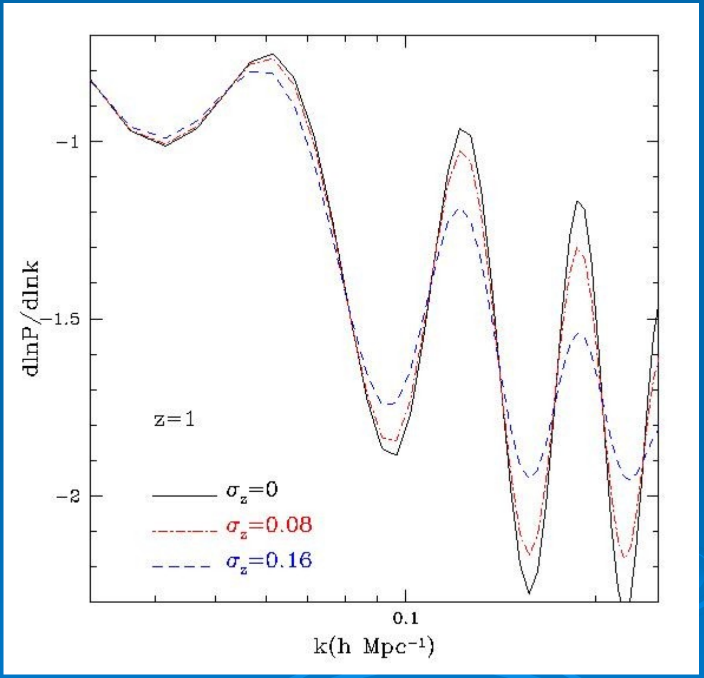
1000 small-core fibers to replace existing (more objects, less sky contamination)



LBNL CCDs + new gratings improve throughput
Update electronics + DAQ

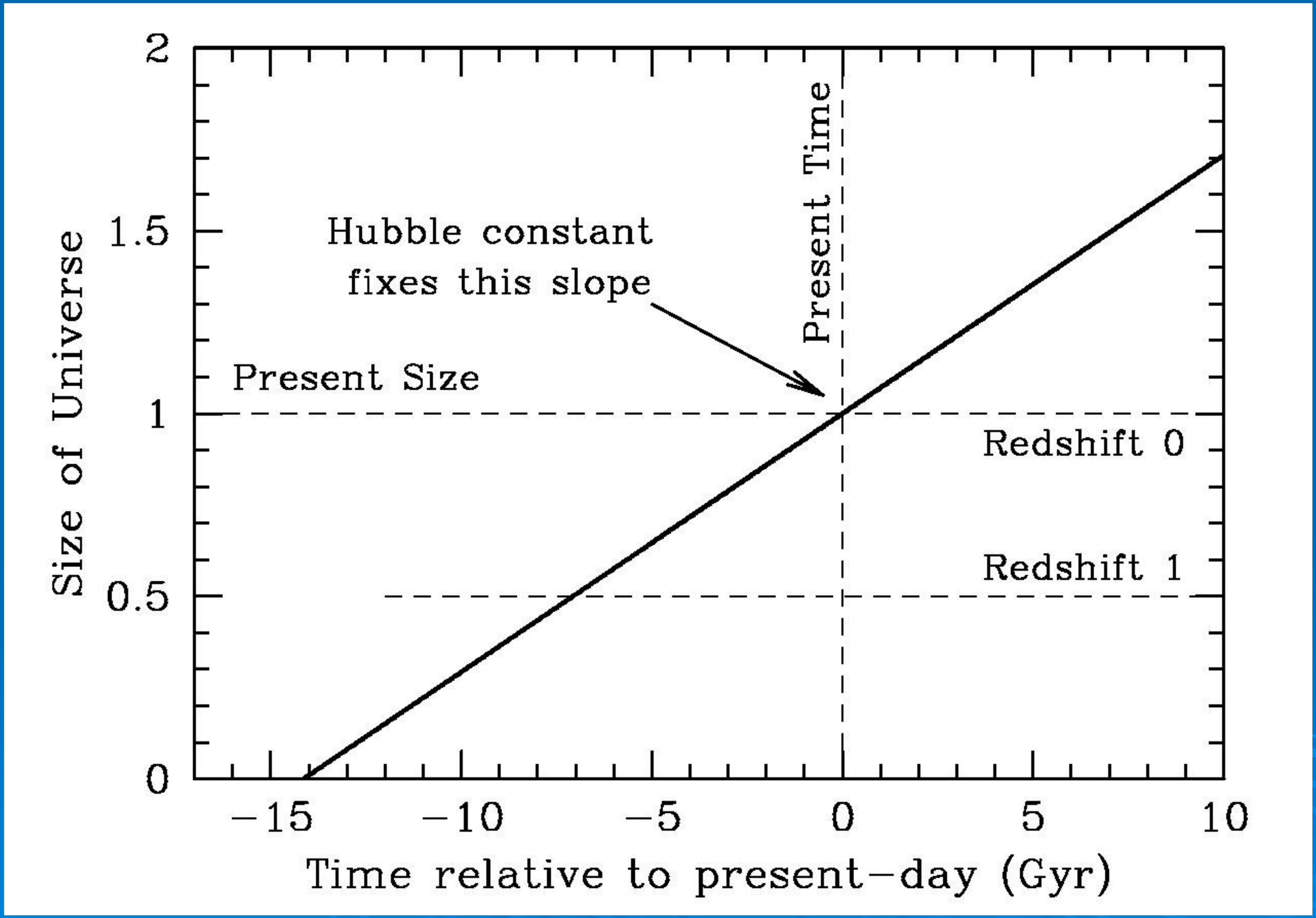
Photometric Redshifts?

- Can we do this without spectroscopy?
- Measuring H(z) requires detection of acoustic oscillation scale along the line of sight.
  - Need ~10 Mpc accuracy. n$_z$~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.

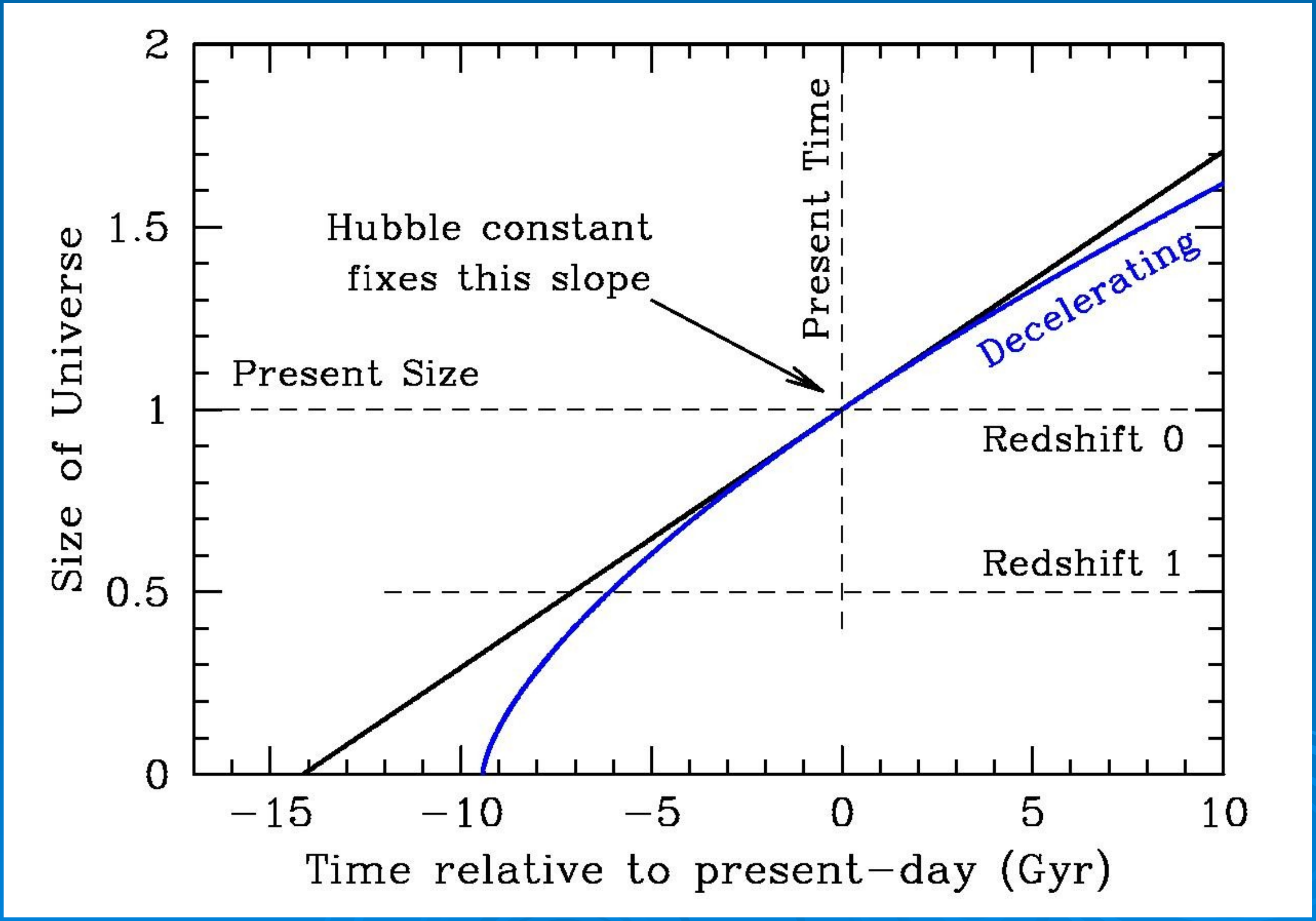


4% photo-z's don't smear the acoustic oscillations.

Distances to Acceleration



Distances to Acceleration



Distances to Acceleration