Dark Energy and Cosmic Sound

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Outline

- Quick introduction to dark energy.
- Baryon acoustic oscillations (BAO) as a standard ruler.
  - Linear theory pedagogy.
  - Non-linear structure formation.
- Detection of the acoustic signature in the SDSS Luminous Red Galaxy sample.
  - Cosmological constraints therefrom, including a summary of the new DR7 results.
- Large galaxy surveys at higher redshifts as a route to 1% distances and better.
  - Introduce SDSS-III.
What is the Universe Made Of?

- The composition of the Universe is a basic question of physics, and one that has turned out to have surprising answers!

Image from the Deep Lens Survey
Weighing the Universe with Distance Measurements

Hubble constant fixes this slope

Present Size

Redshift 0

Redshift 1

Time relative to present-day (Gyr)

Size of Universe
Weighing the Universe with Distance Measurements

![Graph showing the relationship between size of the Universe and time relative to the present-day. The graph includes annotations such as "Hubble constant fixes this slope", "Present Size", "Redshift 0", and "Redshift 1."
Weighing the Universe with Distance Measurements

Hubble constant fixes this slope

Present Size

Accelerating Universe has more Lookback time & distance

Redshift 0

Redshift 1

Time relative to present-day (Gyr)

Size of Universe
Dark Energy

- In 1998, two groups argued from supernova data that the expansion rate of the Universe is accelerating!
- Many possible explanations have been advanced.
  - Cosmological constant
  - New low-mass field(s)
  - Modification to gravity
  - Extra dimensions
  - Your favorite here
- All are exotic, and none is so aesthetically compelling as to be the obvious preference.
- What more can we do observationally?
  - Main path is very accurate distance measurements, 1% and better!
Quick Cosmology Jargon

- The size of the Universe is $a(t)$, aka the scale factor.
- Light is stretched in wavelength by $1 + z$, where $1 + z = a(t_{\text{obs}})/a(t_{\text{emit}})$. $z$ is called the redshift.
- $z$, $a$, and $t$ are all used as time coordinates.
- The Hubble constant is the proportionality between expansion velocity and distance (for local objects). $H(t) = d(\ln a)/dt$.
- We write the present-day value as $H_0 = 100h$ km/s/Mpc.
- There is a critical density at which gravity would asymptotically halt the expansion. $\rho_{\text{crit}} \sim H^2$.
- $\Omega_m$ is the matter density divided by the critical density. Includes gas (baryons) and cold dark matter (CDM). Other quantities are similar, e.g., $\Omega_b$ for baryons.
- The proper matter density today is proportional to $\Omega_m h^2$.
- Time evolution of dark energy parameterized as $w(z)$. $w = -1$ is a cosmological constant.
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 $t_{\text{rec}}$ affects late-time amplitude.

Big Bang

Ionized

Recombination
$z \sim 1000$
$
\sim 400,000 \text{ years}$

Neutral

Today

Time
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 superposition 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.
- This effect is known as the baryon acoustic oscillation, or BAO.
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 $D_A(z)$! 

\[ \delta r = D_A \delta \theta \]
\[ \delta r = (c/H) \delta z \]

Observer
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.
Measuring the Acoustic Peak

- Aggressive surveys could reach precisions around 0.2% in distance. Can we achieve this?

- Three broad classes of systematic errors:
  - Observational: Selection functions, window functions, survey homogeneity, redshift errors, etc.
  - Astrophysical: Non-linear structure formation, galaxy clustering bias, errors in modeling redshift distortions
  - Cosmological: Some exotic dark sector deviation, e.g., to alter the sound horizon.

- Overall, we expect to be statistics limited.
Cosmological Effects

- Non-standard high-redshift physics can alter the sound horizon or the shape of the power spectrum.
  - E.g., decaying dark matter, alterations to recombination, subdominant isocurvature modes.
  - However, these models are usually strongly constrained by the CMB before they reach a level that affects low-redshift BAO.

- Note that alterations to the sound horizon is a particular one-parameter deviation at low redshift.

- These should be considered as discovery space.
Observational Effects

- Study of observational systematics in the clustering analysis of galaxy surveys is an old topic. Extensive work over the last 30 years.
  - Many methods for diagnosing, removing, and avoiding systematic effects.

- The BAO application is much easier than general P(k) because the BAO signature is oscillatory and hence strongly differential in scale.
  - Observational effects are nearly always broadband, and we simply marginalize against general broadband terms.

- Wavenumber scale is tied directly to measurement of angles and redshifts, which are much better than $10^{-3}$. 
Astrophysical Effects

- 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.
- Moving the scale requires net infall on 150 Mpc scales.
  - This depends on the overdensity inside the sphere, which is about $J_3(r) \sim 1\%$.
  - Over- and underdensities cancel, so mean shift is <0.5%.
  - Simulations confirm that the shift is <0.5%.

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)
BAO in Simulations

- Seo et al (2008, 2009) used up to $472 h^{-3} \text{Gpc}^3$ of new simulations to look at the shift of the acoustic scale.
- Analysis uses linear power spectrum with 8-10 broadband marginalization terms.
  - $P(k) = B(k) P_{\text{linear}}(ak) + A(k)$, where $B(k)$ and $A(k)$ are low-order smooth functions. We measure $\alpha$ to get acoustic scale.
- Find shift of 0.2-0.3% in the matter $P(k)$.
  - This is not a systematic error, but rather a small correction that one computes and applies.
  - Padmanabhan & White (2009) presents a derivation from 2nd-order perturbation theory.

- Reconstruction removes the shift to <0.03%. Measuring the large scale density field gives an accurate prediction for the large-scale flows.

Seo, Siegel, DJE, & White (2008)
Seo et al. (2009)
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 $H$. 
Cosmic Variance Limits

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

Black: Linear theory
Blue: Non-linear theory
Red: Reconstruction by 50% (reasonably easy)

Seo & DJE (2008)
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Seo & DJE (2008)
Chasing Sound Across Redshift

Distance Errors versus Redshift
The Sloan Digital Sky Survey

- The SDSS is the world’s largest galaxy redshift survey.
- Took digital pictures of one quarter of the sky in 5 bandpasses.
  - Over 350 million objects.
- Then performed spectroscopy of 1.5 million objects, mostly galaxies.
SDSS Luminous Red Galaxies

200 kpc
Detection of the Acoustic Peak

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

Eisenstein et al. (2005)
Cosmological Constraints

Eisenstein et al. (2005)
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, each with <10% precision.
- $\Omega_m = 0.273 \pm 0.025 + 0.123(1+w_0) + 0.137\Omega_K$. 
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, 2009), Reid et al. (2009)

The results are highly consistent.

DR7 result reaches 2.7% error.

Tegmark et al. (2006)
Power Spectrum

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BAO in SDSS-II DR7

- Percival et al. (2009) analysis of BAO signature in SDSS-II (LRG+MAIN) and 2dF GRS.
- Reid et al. (2009) analysis of LRG power spectrum, including halo compression and quasi-linear corrections to use the broadband power spectra.
- Both use FKP P(k) techniques.
- DR7 covers 7900 sq deg and has about 110K LRGs, a little more than twice the Eisenstein et al. (2005) data set.

Percival et al. (2009)
BAO Distance Measurements

- Percival et al. (2009) fits a distance-redshift relation held at \( z = 0.2 \) and 0.35.

- Can express result as
  - \( r_s/D_{\nu}(0.275) = 0.1390 \pm 0.0037 \) (2.7%), and
  - \( D_{\nu}(0.35)/D_{\nu}(0.20) = 1.736 \pm 0.065 \)
    - LCDM is 1.67, so only 1-sigma away; EdS is 1.55.

- \( D_{\nu}(0.275) = 1104 \pm 30 \text{ Mpc} \)
  \[ x(\Omega_m h^2/0.1326)^{-0.25} \]
  \[ x(\Omega_b h^2/0.02273)^{-0.134} \]
Low-redshift constraints

- Using this standard ruler and CMB constraints on the matter and baryon density, we can use the standard ruler to measure $H_0$ and hence $\Omega_m$.
  - $\Omega_m = (0.282 \pm 0.018)$
    - $x (\Omega_m h^2/0.1326)^{0.58}$
    - $x [1+0.25\Omega_k+0.23(1+w_0)]$
  - $H_0 = (68.6 \rightarrow 2.2 \text{ km/s/Mpc})$
    - $x (\Omega_m h^2/0.1326)^{0.21}$
    - $x [1-0.13\Omega_k-0.12(1+w_0)]$
- This depends only the low-z distance scale.

Percival et al. (2009)
Combination with WMAP & SNe

- Good consistency between the three data sets and between the two analyses. “Tensions” are not statistically significant.
- Models that are both non-flat and have constant $w$ give overlap at flat LCDM.
  - $\Omega_K = -0.006 \pm 0.008$
  - $w = -0.97 \pm 0.10$
  - $\Omega_m = 0.290 \pm 0.019$
  - $H_0 = 67.6 \pm 2.2$ km/s/Mpc

Percival et al. (2009)
Seeing Sound in the Lyman $\alpha$ Forest

- The Ly$\alpha$ forest tracks the large-scale density field, so a grid of sightlines should show the acoustic peak.
- This may be a cheaper 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)
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.
- Support from Sloan Foundation, DOE, NSF, and over 40 member institutions.
Baryon Oscillation Spectroscopic Survey (BOSS)

- Definitive study of the low-redshift acoustic oscillations. 10,000 deg² 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 D & H at 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 constraints:
  - Dark energy parameters $w_p$ to 2.8% and $w_a$ to 25%.
  - Hubble constant $H_0$ to 1%.
  - Matter density $\Omega_m$ to 0.01.
  - Curvature of Universe $\Omega_k$ to 0.2%.
  - Sum of neutrino masses to 0.13 eV.

- Superb data set for other cosmological tests, including redshift distortion and equality scale measurements, as well as diverse extragalactic applications.
BOSS Instrumentation

- BOSS has upgraded the old SDSS spectrograph.
  - Increase to 1000 fibers, decrease to 2” aperture.
  - Better CCDs & gratings to improve throughput.
  - Installed and commissioned July-September 2009.
Survey running since December. Already 115,000 survey-quality observations of galaxies!
Multi-object APO Radial-Velocity Exoplanet Large-area Survey (MARVELS)

- 15 years of study of planets around other stars has revealed significant surprises, such as the large population of hot Jupiters.
- Current searches are heterogeneous. Small statistical samples make it difficult to test planet formation theories.
- MARVELS uses the 7 sq deg field of the Sloan telescope to observe 60 bright stars simultaneously. This will allow us to build a large and statistically robust sample.


60 simultaneous spectra with existing KET at Sloan 2.5-meter.
SEGUE-2: Probing the Outer Milky Way

- SEGUE-2 will map the dynamical and nucleosynthetic history of the thick disk and halo.
  - 114,000 optical spectra of faint stars were observed over the last year. Data is being analyzed in combination with the SEGUE and SDSS datasets.
- Discovery & exploration of tidal streams: long-lived kinematic signatures of the formation of the Milky Way.
- 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.

- APOGEE will study the whole Galaxy with a new high-resolution infrared (1.6 $\mu$m) spectrograph.
  - 300 fibers, $R=25,000$ 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 $\mu$m permits work with warm fibers. IR detectors finally large enough to get significant spectral range. Targets from 2MASS.
  - CDR passed in August 2009; construction underway!

- Ground-breaking sample of 100,000 stars, mostly giants.
  - 100 times more high-signal-to-noise, high-res spectroscopy than world's current collection.

- Common abundance scale across all parts of Galaxy.
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, Besancon)
- German Participation Group (AIP, MPE, MPIA, ZAH)
- Instituto de Astrofisica de Canarias
- Instituto de Astrofisica de Andalucia, Granada *
- IFIC-CSIC Valencia
- ICREA Barcelona
- 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
- Texas Christian University
- Univ. of Tokyo
- Univ. of Utah
- Vanderbilt University
- Univ. of Virginia
- Univ. of Washington
- University of Wisconsin
- Yale University
- Italics indicate smaller members
We’ve Only Just Begun

- SDSS-II LRG has only surveyed only $10^{-3}$ of the volume of the Universe out to $z \sim 5$.
- 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.
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.
  - Independent method with good precision.

- SDSS uses the acoustic signature to measure $D_A(z=0.275)/D_A(z=1000)$ to 2.7%.

- Larger galaxy surveys such as SDSS-III/BOSS will push to 1% and below across a range of redshift.