SDSS-III, Baryon Oscillations and Dark Energy

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Dark Energy is Mysterious

- Observations suggest that the expansion of the universe is presently accelerating.
  - Normal matter doesn’t do this!
  - Requires exotic new physics.
    - Cosmological constant?
    - Very low mass field?
    - Some alteration to gravity?

- We have no compelling theory for this!
  - Need observational measure of the time evolution of the effect.
The homogeneous metric is described by two quantities:

- The size as a function of time, \( a(t) \). Equivalent to the Hubble parameter \( H(z) = d \ln(a)/dt \).
- The spatial curvature, parameterized by \( \Omega_k \).

The distance is then

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

(\text{flat})

\( H(z) \) depends on the dark energy density.
Dark Energy is Subtle

- Parameterize by equation of state, $w = p/\rho$, which controls how the energy density evolves with time.
- Measuring $w(z)$ requires exquisite precision.

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

Comparing Cosmologies
Outline

- Baryon acoustic oscillations as a standard ruler.
- Detection of the acoustic signature in the SDSS Luminous Red Galaxy sample at $z=0.35$.
  - Cosmological constraints therefrom.
- Large galaxy surveys at higher redshifts.
  - Future surveys could measure $H(z)$ and $D_A(z)$ to better than 1% from $z=0.3$ to $z=3$.
- Present the Baryon Oscillation Spectroscopic Survey and SDSS-III.
Although there are fluctuations on all scales, there is a characteristic angular scale.
Acoustic Oscillations in the CMB

WMAP team (Bennett et al. 2003)
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.
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 weak, because it is only a baryon signal and is dispersed to a large radius.
- Hence, you do not expect to see bullseyes in the galaxy distribution.
- Instead, we get a 1% bump in the correlation function.
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
Acoustic Oscillations, Reprise

- Divide by zero-baryon reference model.
- Acoustic peaks are 10% modulations.
- Requires large surveys to detect!

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
- Do these affect the acoustic signatures?
Nonlinearities & Bias

- Non-linear gravitational collapse partially smears out the signature (more later).
- Clustering bias and redshift distortions alter the power spectrum but don’t create preferred scales at 150 Mpc!
- Acoustic peaks expected to survive mostly intact.

Meiksen & White (1997), Seo & DJE (2005)
Virtues of the Acoustic Peaks

- The acoustic signature is created by physics at $z=1000$ when the perturbations have an amplitude of $10^{-4}$. 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 $H$. 
Introduction to SDSS LRGs

- SDSS uses color to target luminous, early-type galaxies at 0.2<z<0.5.
  - Fainter than MAIN (r<19.5)
  - About 15/sq deg
  - Excellent redshift success rate
- The sample is close to mass-limited at z<0.38. Number density ~ 10^{-4} h^3 Mpc^{-3}.

Science Goals:
- Clustering on largest scales
- Galaxy clusters to z~0.5
- Evolution of massive galaxies
Redshift Distribution

55,000 galaxies for this analysis; about 100k now available.
Large-scale Correlations

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

Pure CDM model has no peak.

Warning: Correlated Error Bars
Another View

CDM with baryons is a good fit:

$$\chi^2 = 16.1 \text{ with } 17 \text{ dof.}$$

Pure CDM rejected at $$\Delta \chi^2 = 11.7$$
A Prediction Confirmed!

- Standard inflationary CDM model requires acoustic peaks.
  - Important confirmation of basic prediction of the model.

- This demonstrates that structure grows from $z=1000$ to $z=0$ by linear theory.
  - Survival of narrow feature means no mode coupling.
Two Scales in Action

Equality scale depends on $(\Omega_m h^2)^{-1}$.

Acoustic scale depends on $(\Omega_m h^2)^{-0.25}$.

\[ \Omega_m h^2 = 0.12 \]
\[ \Omega_m h^2 = 0.13 \]
\[ \Omega_m h^2 = 0.14 \]
Parameter Estimation

- Vary $\Omega_m h^2$ and the distance to $z = 0.35$, the mean redshift of the sample.
  - Dilate transverse and radial distances together, i.e., treat $D_A(z)$ and $H(z)$ similarly.
- Hold $\Omega_b h^2 = 0.024$, $n = 0.98$ fixed (WMAP-1).
  - Neglect info from CMB regarding $\Omega_m h^2$, ISW, and angular scale of CMB acoustic peaks.
- Use only $r > 10 h^{-1}$ Mpc.
  - Minimize uncertainties from non-linear gravity, redshift distortions, and scale-dependent bias.
- Covariance matrix derived from 1200 PTHalos mock catalogs, validated by jack-knife testing.
Cosmological Constraints

- Pure CDM degeneracy
- Acoustic scale alone
- WMAP 1σ
A Standard Ruler

- If the LRG sample were at $z=0$, then we would measure $H_0$ directly (and hence $\Omega_m$ from $\Omega_m h^2$).
- Instead, there are small corrections from $w$ and $\Omega_\kappa$ to get to $z=0.35$.
- The uncertainty in $\Omega_m h^2$ makes it better to measure $(\Omega_m h^2)^{1/2} D$. This is independent of $H_0$.
- We find $\Omega_m = 0.273 \pm 0.025 + 0.123(1+w_0) + 0.137 \Omega_\kappa$. 
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.
- $\Omega_m = 0.273 \pm 0.025 + 0.123(1+w_0) + 0.137 \Omega_K$. 

Constant $w$ Models

- For a given $w$ and $\Omega_m h^2$, the angular location of the CMB acoustic peaks constrains $\Omega_m$ (or $H_0$), so the model predicts $D_A(z=0.35)$.

- Good constraint on $\Omega_m$, less so on $w$ ($-0.8 \pm 0.2$).
Common distance scale to low and high redshift yields a powerful constraint on spatial curvature:

$$\Omega_K = -0.010 \pm 0.009 \quad (w = -1)$$
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.

- $\Omega_m = 0.25$, in part due to WMAP-3 vs WMAP-1.

Tegmark et al. (2006)
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 $k \sim 0.2 h \text{ Mpc}^{-1}$ ($\lambda = 30 \text{ Mpc}$)
- Require several Gpc$^3$ of survey volume with number density few $\times 10^{-4}$ comoving $h^3 \text{ Mpc}^{-3}$, typically a million or more galaxies!
- No heroic calibration requirements; just need big volume.
- Discuss design considerations, then examples.
Non-linear gravitational collapse and galaxy formation partially erases the acoustic signature.

This limits our ability to centroid the peak and could in principle shift the peak to bias the answer.

Meiksen & White (1997), Seo & DJE (2005)
Nonlinearities in 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.
- Moving the scale requires net infall on 100 \( h^{-1} \) Mpc scales.
  - This depends on the over-density 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)
Where Does Displacement Come From?

- Importantly, most of the displacement is due to bulk flows.
  - Non-linear infall into clusters "saturates". Zel'dovich approx. actually overshoots.

- Bulk flows in CDM are created on large scales.
  - Looking at pairwise motion cuts the very large scales.

- The scales generating the displacements are exactly the ones we're measuring for the acoustic oscillations.

DJE, Seo, Sirko, & Spergel, 2007
Fixing the Nonlinearities

- Because the nonlinear degradation is dominated by bulk flows, we can undo the effect.
- Map of galaxies tells us where the mass is that sources the gravitational forces that create the bulk flows.
- Can run this backwards.
- Restore the statistic precision available per unit volume!

DJE, Seo, Sirko, & Spergel, 2007
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, 2007
Cosmic Variance Limits

Errors on $H(z)$ 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, 2007
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)

Neutral H absorption observed in quasar spectrum at $z=3.7$
Chasing Sound Across Redshift

Distance Errors versus 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)

- 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 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 $\Omega_m$ 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, as well as diverse extragalactic applications.
BOSS Quasar Survey

- The large-scale clustering of the intergalactic medium should also show the acoustic signature.
- A dense grid of quasars can reveal the 3-d clustering of the Ly$\alpha$ forest.
- BOSS will observe 160,000 $z > 2.2$ quasars to study the BAO at $z > 2$ with Ly$\alpha$ forest tomography.
  - Measure distance to and $H(z)$ at $z = 2.3$ to 1.5%.
  - Powerful constraint on spatial curvature and high-redshift dark energy.
  - 20% piggyback program on BOSS galaxies.
- Success would have ongoing impact: cheapest way to do $z > 2$ BAO. Each quasar gives 100's of data points along line of sight.
- Also quasar science at the peak of QSO activity. Double the quasars at $z > 4$ and $z > 6$. 
BOSS Redshift Distributions

![Graphs showing redshift distributions for quasars and galaxies. The left graph represents the distribution of quasar densities across different redshifts, while the right graph shows the distribution of redshifts for galaxies, indicated by their density per degree squared.]
BOSS Parameter Errors
BOSS Power Spectrum

\[ P(k) \ [h/Mpc]^3 \]

- \( \Lambda \text{CDM} \)
- \( n_s = 1.0 \)
- \( \Omega_\nu = 0.01 \)
### DETF Figure of Merit

<table>
<thead>
<tr>
<th>Experiment</th>
<th>DETF FOM</th>
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</thead>
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<tr>
<td>Stage II + Planck</td>
<td>67</td>
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<tr>
<td>+ BOSS LRG BAO</td>
<td>97</td>
</tr>
<tr>
<td>+ BOSS QSO BAO</td>
<td>144</td>
</tr>
<tr>
<td>+ BOSS Galaxy power spectrum</td>
<td>270</td>
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</tbody>
</table>

- Powerful Stage III data set.
- High complementarity with future weak lensing and supernova data sets.
- **Other Proposed Surveys:**
  - Wiggle\_z  67
  - HETDEX  70
  - WFMOS  94
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.
- 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
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 heterogeneous. 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.


60 simultaneous spectra with existing KET at APO 2.5-meter.
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.
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 leave long-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 $\mu$m) 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 $\mu$m permits work with warm fibers. IR detectors finally large enough to get significant spectral range.

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

- Common abundance scale across all parts of Galaxy.
APOGEE Science

- APOGEE will study the chemical and kinematic fingerprints of the buildup of the Galaxy.
  - 0.5 km/s velocity precision will map subtle dynamical perturbations of the Galactic disk.
  - Nucleosynthetic tags of different substructures.
  - Detailed study of the bulge; can study chemical enrichment of the early progenitors of the MW.

Font et al. (2005)
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.
  - Much sooner than WFMOS.

- 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.
  - APOGEE can be sooner and cheaper.
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 Letters of Interest

- Univ. of Arizona
- Cambridge Univ.
- Case Western Univ.
- Univ. of Florida
- French Participation Group
- Univ. of Heidelberg
- Johns Hopkins Univ.
- Korean Institute for Advanced Study
- Lawrence Berkeley Lab
- Los Alamos National Lab
- MPA Garching

- 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 Virginia
- Univ. of Washington
- Others welcome!
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 LRG sample uses the acoustic signature to measure $D_A(z=0.35)/D_A(z=1000)$ to 4%.

- Larger galaxy surveys are feasible in the coming decade, push to 1% across a range of redshift.

- SDSS-III will pursue large surveys on 3 major themes. Collaboration forming now.
Distances to Acceleration

The graph shows the size of the universe over time relative to the present-day. The Hubble constant fixes the slope of the line. Key markers include the present size, time, and redshifts 0 and 1.
Distances to Acceleration

- Hubble constant fixes this slope
- Present Size
- Present Time
- Redshift 0
- Redshift 1

Size of Universe vs. Time relative to present-day (Gyr)
Distances to Acceleration

Hubble constant fixes this slope

Present Size

Accelerating Universe has More Lookback Time & Distance

Time relative to present-day (Gyr)

Size of Universe

-15 -10 -5 0 5 10

Present Time

Redshift 0

Redshift 1

Accelerating

Decelerating