Cosmology from a Redshift Survey of 200 Million Galaxies

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Overview

Cosmological observations have been stunningly successful in revealing the large-scale properties of our universe. We now have a standard model of cosmology that is supported by a tightly interlocking web of diverse measurements. Many long-standing questions have been definitively answered, but important questions remain: Is the current standard model of cosmology correct? What is the dark energy? Is General Relativity correct on the largest scales? Did the universe begin with inflation, and if so, what kind? In this white paper we suggest that **a spectroscopic galaxy redshift survey 100-fold larger than those underway** can offer unprecedented power in addressing critical cosmological questions. A $0.7 \leq z \leq 2$ spectroscopic redshift survey of ~ 200 million galaxies over the full available extragalactic sky would cover an effective volume of ~ 200 Gpc^3, a vastly larger sample of our universe than any existing galaxy redshift survey. The resulting data set would be an important legacy for astrophysics and cosmology. An enormous galaxy redshift survey, perhaps as part of the *Joint Dark Energy Mission* (*JDEM*), would offer a powerful opportunity to address all of the key cosmological questions enumerated above.

Introduction

Galaxy redshift surveys have a long and successful history in astronomy and cosmology. Hubble's 1929 discovery of the expansion of the universe was rooted in the spectra of a handful of nearby galaxies. The CfA galaxy redshift survey was the first large-scale 3-D view of cosmological distances. It dramatically showed that galaxies lie on the surfaces of bubble-like structures, with superclusters of galaxies at their junctions. The gravitational potential field was inferred and compared with N-body simulations, and cosmologists developed and refined 2-, 3-, and 4-point correlation function techniques to analyze these data. The Las Campanas Redshift Survey further expanded our view of the universe. Currently, the two leading recent galaxy redshift surveys are the *2-degree Field Galaxy Redshift Survey* (*2dFGRS*) and the *Sloan Digital Sky Survey* (*SDSS*). These were used to detect the long-predicted signature of baryon acoustic oscillations (BAO).

Figure 1 shows the depth and breadth of these redshift surveys. Measurement of large-scale structure, whether by galaxy and quasar surveys, weak lensing, or IGM absorption, is our most powerful tool in low-redshift cosmology. Obtaining accurate redshifts is the only way to reveal the richness of the universe in 3-D. We suggest that the time is right for an enormous step forward. A large new galaxy redshift survey is needed, and in this white paper we refer to *JDEM* as an example of an opportunity to achieve it.

Measurement of the Matter Power Spectrum

A galaxy redshift survey of unprecedented effective cosmic volume would provide an impressive measure of the matter power spectrum $P(k)$. If the effects of bias and nonlinear growth are sufficiently well-modeled and understood, then the power spectrum strongly constrains the background cosmological model. Here we focus on the redshift range $0.7 < z < 2$, suitable for JDEM, although surveys at other redshifts are also of high value.

The transition to non-linearity begins at about $k \sim 0.3\ h$ Mpc^{-1}, so for $k_{\max} = 0.3\ h$ Mpc^{-1}, the galaxy redshift survey measures ~ 20 million modes in the linear regime. This corresponds to a 0.03% measurement of linear theory, and superb measurements of the non-linear regime. Even after marginalization over redshift distortions, this will produce stunningly good measurements of the projected correlation function. The quasi-linear regime at scales above a few Mpc is fully accessible to accurate modeling. Because it is in 3-D, a *JDEM* galaxy redshift survey will measure

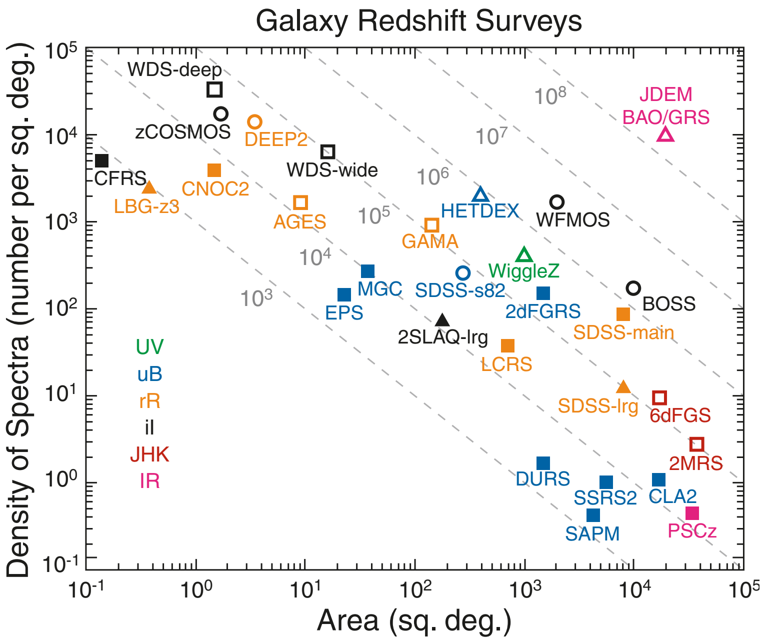

Figure 1: A *JDEM* galaxy redshift survey would be a substantial advance over previous surveys. Galaxy redshift surveys are plotted as a function of their source density depth and survey area breadth. The color of each point provides the source selection wavelength. Squares are magnitude-limited surveys; circles are surveys that use color cuts for photometric redshift selection; and triangles are highly targeted surveys. Filled symbols are completed surveys. An estimate of the total number of galaxy redshifts is shown by the dashed diagonal lines. (Figure adapted from original by I. Baldry.)

more linear modes than even ambitious weak lensing experiments like *LSST* and even more than the *Planck* mission will measure for the CMB. Of course, the *JDEM* galaxy redshift survey will primarily probe a different($z > 0.7$) volume from *LSST*'s weak lensing data.

The survey would have important and broad applications. To name just a few, the *JDEM* galaxy redshift survey will: (1) measure the shape of the galaxy clustering power spectrum to improve $\Omega_m h^2$; (2) improve the measurement of the neutrino mass, especially when combined with *Planck* data; (3) determine the nonlinear onset as a measure of the growth function; (4) help the search for isocurvature modes, especially when combined with *Planck* CMB measurements; (5) be able to detect features in the primordial power spectrum produced by the inflaton potential, trans-Planckian physics, or the effects of inhomogeneous reionization; and (6) measure the BAO peak position in the power spectrum to improve our measurements of basic cosmological parameters.

Baryon Acoustic Oscillations (BAO)

All of the structure in the universe observed today was initially seeded by primordial density fluctuations in the early universe. Initial regions of overdensity were also regions of greater than average pressure. These over-pressured regions drove the expansion of spherical sound waves. In particular, photons, electrons, and the baryon gas acted as a single fluid until the expansion and cooling of the universe reached the epoch of decoupling, leaving an extra abundance of baryons in a spherical shell around the initially overdense regions. The photons freely streamed away.

The sky is filled with these spherical shells of baryons with fixed radii of 148 comoving Mpc, corresponding to the size of the horizon at decoupling. *WMAP* measured this radius with high precision by mapping the CMB over the full sky (Bennett et al. 2003; Komatsu et al. 2008). The power spectrum of the map shows the series of oscillatory peaks and troughs from the BAO.

WMAP provides the BAO calibration, with improvements to come from *Planck*. This establishes a “standard ruler” against which the universe can be measured (Eisenstein & Bennett 2008). The shells of gas around the initial overdense locations enhance the probability that galaxies formed with separations on the BAO scale. In 2005, the expected $\sim 1\%$ excess galaxy correlation was observed at the expected scale, both by the *2dFGRS* and the *SDSS* galaxy redshift survey (Cole et al. 2005; Eisenstein et al. 2005). The combination of the *WMAP*, *SDSS*, and supernovae data places the tightest constraints to date on the nature of the dark energy (Komatsu et al. 2008).

Since the excess of galaxy correlations at the BAO scale is only enhanced by $\sim 1\%$, the use of the BAO to probe dark energy requires that accurate redshifts and positions of large numbers of galaxies be observed over large regions of the sky. However, the acoustic scale of 148 Mpc is so much larger than the scale of non-linear structure formation that the scale remains a robust standard ruler at low redshift.

The power of the BAO signature to probe dark energy has prompted many groups to propose and carry out ground-based spectroscopic BAO measurements. *WiggleZ*, *WFMOS*, *HETDEX*, and the *Baryon Oscillation Sky Survey* (*BOSS*; a part of *SDSS-III*) are the most aggressive efforts currently under development and will yield 1% distance measurements using the BAO as a standard ruler. Figure 2 shows how a *JDEM* galaxy redshift survey can reach superb distance precisions, reaching an aggregate of 0.1%. The *JDEM* measurements will measure distances, and hence the expansion history, at redshifts that are highly challenging for ground-based observations. Distance measurements using Type Ia supernovae are ultimately limited by flux calibration accuracy so even with aggressive efforts, the high redshift BAO are expected to be superior for delineating the expansion history. However, at low redshifts ($z < 0.6$ or so), the Type Ia SNe are unmatched due to the limited cosmic volume available to both BAO and weak gravitational lensing methods.

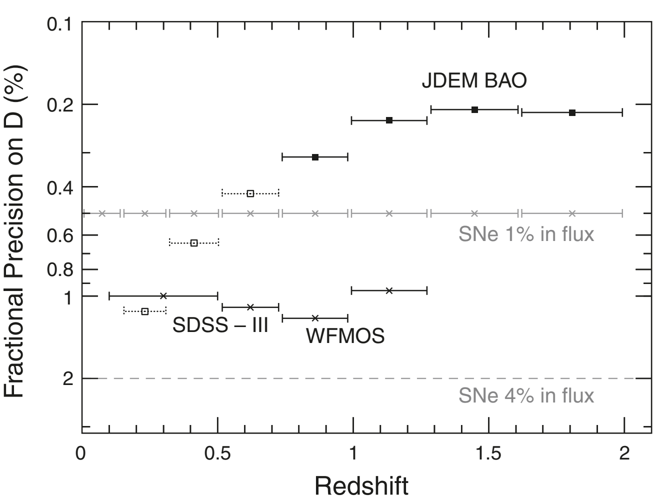

Figure 2: The fractional error on the distance determination shows that a *JDEM* galaxy redshift survey will complement existing ground-based BAO surveys and extend accurate distance determination to much higher redshifts. *Note that lower distance errors are higher up on this plot and that the scale is logarithmic.* Lines corresponding to 1% and 4% errors in flux measurements of a standard candle are also shown; this argues that BAO is preferred at high redshift while SNe are preferred at low redshift. This figure does not show the important leverage that comes from the radial BAO measurement of $H(z)$.

Tangential and Radial BAO: Observations of the spherical sound wave are possible both along and across the line of sight. The angle subtended by a standard ruler at redshift z transverse to the line of sight yields a measurement of the angular diameter distance d_A. The angular diameter distance is equivalent to the luminosity distance, as $d_L = (1+z)^2 d_A$. The angular diameter distance is robustly based on the geometry between the observer and the horizon, and *JDEM* could measure an aggregate d_A precision of 0.1%.

A standard ruler at redshift z arranged along the line of sight corresponds to a change in redshift Δz. This yields a measurement of the Hubble parameter $H(z)$, which is a direct measurement of the expansion history of the Universe. In General Relativity, $H(z)$ is immediately related to the dark energy density as a function of redshift. At high redshift, the tangential BAO is primarily a measurement of the curvature of the Universe, while the radial BAO is where most of the leverage on dark energy arises. *The ability of BAO to measure $H(z)$ directly at high redshift is an important advantage of the method.* *JDEM* could measure an aggregate $H(z)$ of 0.2%, corresponding to a 3% fractional measurement of the dark energy density at $z \approx 1.5$.

We stress that spectroscopic redshifts are required to extract any of the radial BAO signature and most of the tangential BAO signature. A redshift survey of most of the sky at a sampling density of around 10^{-3} Mpc^{-3} is needed to extract the cosmic variance limited information from the BAO.

BAO Sytematics According to the Dark Energy Task Force, "This is the method least affected by systematic uncertainties...," and, "It is less affected by astrophysical uncertainties than other techniques." The BAO is the only approach that the NRC's Beyond Einstein Program Assessment Committee (BEPAC) called "very robust."

Importantly, the control of observational systematics for the BAO measurement are not challenging. The measurements require only spectroscopic galaxy redshifts and positions, two of the least demanding and best established measurements in astrophysics. One needs to monitor the survey selection function, but because the BAO is a differential signature as a function of scale, most errors in survey selection cancel out. The redshift precision need only correspond to 300 km/s, and catastrophic errors at levels even up to 10% can be handled. The BAO is challenging because of the large survey volumes required, not because of the fine control of the observations.

Instead, the systematic errors of concern are astrophysical:

Non-linear structure formation can affect the BAO. At low redshift, the BAO signature is partially smeared out, making it harder to centroid. Simulations and theory argue that this is due dominantly to large-scale flows, and the effect can be partially reversed with simple density-field reconstruction techniques. Of more concern is the idea that these large-scale flows might cause the acoustic scale to be shifted. This requires a consistent mean infall on 150 Mpc scales. Simulations of huge cosmic volumes when analyzed with estimators of the acoustic scale that appropriately marginalize over nuisance terms show that this non-linear shift is only 0.2% at z=1. More important, these shifts are accurately calculable and can therefore be removed (Seo et al. 2008).

Galaxy bias could additionally shift the acoustic scale. A linear bias does not cause a shift, as it does not alter the shape of the correlation function. The effect of bias is to alter how the convergent and divergent large-scale flows are labeled with positive or negative weights in the two-point function. Only this relation between the galaxy field and the large-scale velocity field matters. Tests with simple halo occupation models show that the effects are small, again of order 0.2% at z=1. It seems overwhelmingly likely that a redshift survey of this scope would be able to constrain the bias model well enough to correct this 0.2% effect to below the *JDEM* statistical error of 0.1%.

More exotic bias models that extend the dependence on the density field to 10 Mpc scales and beyond, such as imprints from reionization bubbles, might cause a somewhat larger effect. However, these models will also affect other clustering signatures, and an effect large enough to shift the acoustic scale by a large fraction of its total non-linear shift will generically create significant (order unity) alterations in clustering statistics on intermediate scales, where the measurements are phenomenally precise. With the cosmological model now well constrained, cosmological perturbation theory and simulations provide a solid framework with which to discover and control these kinds of bias models.

In short, we expect the *JDEM* BAO measurement to be statistics limited all the way to the cosmic variance limit.

Cosmological exotica, such as a new scalar field that destroys the BAO, are always a danger for measurements that constitute a substantial observational advance, but the fear of exotica is a poor excuse for holding back. On the rare occasions where exotic effects have been discovered, they have tended to be revolutionary discoveries in their own right.

Redshift-Space Distortions

The idea that the cosmological acceleration might be a manifestation of a modification to General Relativity has opened the idea that precise measurements of the growth of structure could distinguish between dark energy models and modified gravity models. One way to measure the growth of structure is to compare the amplitude of clustering measured at two different redshifts (e.g., using weak lensing). However, one can measure the growth directly at a single redshift by using the fact that structure grows because of the flow of matter into overdense regions and that these flows are directly detectable in redshift-space distortions in galaxy clustering. Clustering is statistically isotropic, but it is not measured to be so because the peculiar velocities distort the inferred positions of objects along the line of sight direction (Kaiser 1987). The amount of this anistotropy on large scales is sensitive to the amount of cosmological infall and hence the growth of structure.

Large galaxy redshift surveys offer the opportunity to measure this growth to very high precision. This does require careful modeling of the non-linear velocity field and the effects of galaxy bias, but cosmological simulations give the toolkit required to solve this problem. Redshift distortions provide a route to the measurement of the growth of structure that is comparable to that from weak lensing and cluster counting, with the additional benefit of extending to $z > 1$.

Alcock-Paczynski Test

The Alcock-Paczynski test (Alcock & Paczynski 1979) is based on the fact that a spherical object in real space will appear non-spherical in redshift space if one does not use the correct cosmology. Comparing the extent along and across the line of sight determines the product $H(z)d_A(z)$. The two-point clustering of galaxies is a quantity that should be intrinsically spherical after the redshift-distortion effects are removed. The distortion imprinted from an incorrect cosmology is partially but not fully degenerate with the redshift distortions, and one expects to be able to measure both with sufficiently careful modeling. This is an additional independent test of dark energy and cosmic consistency.

Near-Infrared Imaging

A NIR wide-field space telescope such as *JDEM* could also provide a valuable near-infrared imaging survey that would have a host of astrophysical and cosmological applications. The effective etendue (survey speed) in the infrared for $z > 1$ is between 2 and 3 orders of magnitude greater than current or planned ground-based observatories. Broad-band *JDEM* near-IR images for more than a billion galaxies would be of huge value to astrophysics.

This imaging data can resolve catastrophic degeneracies in photometric redshift surveys (Abdallah et al. 2008) so IR colors from *JDEM*, and the spectroscopic training sample, would make an excellent complement to ground-based photometic redshifts determinations, including for weak gravitational lensing efforts.

A *JDEM* wide-area sky survey in at least two near-IR colors combined with *LSST* or *Pan-STARRS* optical imaging data will provide the community with tools for identifying and studying a broad class of objects ranging from $z > 9$ quasars to nearby T dwarfs. There will be very red objects in the *JDEM* survey that are detected only in the J and H band, with no z band detection. These may include very red stars and very high-z galaxies. These will make excellent candidate objects for *JWST* follow-up, so the *JDEM* survey will enhance the science return from *JWST* by identifying target objects, such as high z quasars and high z galaxies. The galaxy redshift survey will provide a sensitive all-sky search for luminous QSOs at $z > 9$, which will be clearly identified by a spectral break (either in the spectrum, or photometrically with respect to *LSST* photometry). The combination of *LSST*, *Pan-STARRS*, and *DES* optical imaging, *JDEM* near-IR imaging, and *JDEM* spectroscopy will trace galaxy evolution during the critical period between $z = 0.7$ and $z = 2$.

Other Cosmological Scientific Rewards

Missing Baryons: A 200 million galaxy redshift catalog will be a powerful database for studying early universe cosmology. For example, it can constrain the evolution of the "missing baryons." The kinematic S-Z effect arises when the hot electrons in groups and clusters move with a bulk velocity relative to the Hubble flow and Compton scatter the CMB photons. This provides the product of the optical depth and the component of the peculiar cluster velocity along the line of sight, independent of the temperature of the gas, so this is sensitive to all of the ionized baryons. A cross-correlation between *JDEM* galaxies (to provide the velocity information) and microwave maps from *Planck*, the South-Pole Telescope, and the Atacama Cosmology Telescope will give the galaxy-electron-density correlation function and its evolution. Most of the "missing baryons" are thought to be in this gas.

Non-Gaussianity: A *JDEM* galaxy redshift survey would place tighter limits on non-Gaussianity (as quantified by f_{NL}) than the CMB, even with data from *Planck* (e.g., Dalal et al. 2008). The f_{NL} effect in large-scale structure is most significant at low k and is small, so an accurate and sensitive limit requires: (i) a nearly all-sky survey to $z > 1$ to achieve a very large cosmic volume; (ii) selection as far to the red as possible to minimize the effects of Galactic dust; (iii) a survey in three dimensions to check radial versus angular versus checkerboard modes for systematic errors; and (iv) accurate relative calibration. Afshordi & Tolley (2008) find that a *JDEM*-like galaxy redshift survey can constrain $f_{NL} \leq 3$.

Galaxy-CMB Lensing: The galaxy bias factor and matter clustering amplitude can be measured by cross-correlating the *Planck* CMB-lensing signal with the 3-D positions of the *JDEM* galaxies to measure the galaxy-mass cross-correlation function.

Large-Scale Isotropy: While the ΛCDM model is an excellent fit to present data, several papers have presented evidence for deviations from isotropy in the CMB. If real, these deviations would challenge the foundations of modern cosmology and inflation. A full-sky large scale structure survey can be examined for isotropy; comparing many lines of sight would enable distinguishing true anisotropy from redshift-space distortions.

Integrated Sachs Wolfe (ISW) Effect: A correlation analysis of full-sky CMB maps together with the nearly full sky *JDEM* galaxy redshift survey provides a measurement of the Integrated Sachs Wolfe (ISW) effect. This late-time ISW effect is sensitive to the nature of dark energy (Hu & Scranton 2004).

Big Questions

Is the current standard model of cosmology correct? The standard model of cosmology is an excellent fit to a wide range of cosmological data. The CMB and galaxy redshift survey data are two of the most important data sets in constraining the current model. *Planck* will soon produce a significant advance in CMB measurements. A *JDEM* galaxy redshift survey would be a powerful addition to put the standard model to a new and stringent level of testing. Measurements of the angular diameter distance and $H(z)$ from the BAO, the growth rate of cosmic structures from redshift distortions, non-Gaussianity via f_{NL}, and galaxy clustering through $P(k)$ will all combine to put the standard model to its most critical test.

What is the dark energy? The *JDEM* galaxy redshift survey enables multiple tests of dark energy, including a direct measurement of $H(z)$. BAO has enough power to measure the $z > 1$ density of dark energy to 20σ (for a cosmological constant), enough to measure w to 1.5% relative to $z = 0$. The BAO measurements are expected to be particularly robust, with low systematic errors.

Is General Relativity correct on the largest scales? General Relativity on large scales will be tested by a comparison of $H(z)$ (from the BAO) and the growth of structure (from the redshift space distortions due to the peculiar velocities of galaxies near clusters).

Did the universe begin with inflation, and if so, what kind? All of the simplest versions of inflation predict a nearly perfectly flat universe. Current cosmological measurements, when combined, are consistent with a flat universe. Two of the strongest constraints come from the *WMAP* CMB and the *SDSS* BAO measurements. Future *Planck* and *JDEM* BAO measurements will produce a substantial improvement. The *JDEM* data will also be used to place tight limits on f_{NL}, a key discriminator among inflation models.

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