The DOE/HEP Dark Energy Science Program: Status and Opportunities

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The 2011 Nobel Prize was awarded for the discovery of dark energy. DOE's leadership was critical to that achievement, one that has had a tremendous impact on our understanding of fundamental physics. The dark energy is the most direct and dramatic evidence of physics beyond the particle physics Standard Model, which can explain only 5% of the mass-energy content of the Universe. DOE's ongoing leadership in dark-energy projects has resulted in continued observational progress, and we can expect a sustained influx of new results over the next few years.

This Report reviews the current status and the future opportunities for research into the nature of dark energy, focusing on the dark-energy program in the Cosmic Frontiers area of the DOE Office of Science. Early in the next decade a large photometric project, the Large Synoptic Survey Telescope (LSST), with major DOE involvement, will advance the study of weak-lensing dark-energy techniques to the "Stage IV" level. However, it is widely acknowledged that multiple techniques are critical to a successful program of dark energy probes. In this Report we identify several key opportunities that would allow the DOE dark-energy program to attain Stage IV levels for the required multiplicity of techniques. The opportunities we outline will deliver a vibrant program with a continuous stream of results as the next era of dark energy exploration unfolds. Specifically:

1) There is compelling case for an advanced wide-field spectroscopic survey, which would enable dark-energy information at the Stage IV level through the techniques of Baryon Acoustic Oscillations and Redshift Space Distortions. A spectroscopic survey would produce important dark-energy science results in the period between the completion of the Stage III Dark Energy Survey (DES) photometric project and the arrival of results from the Stage IV LSST photometric project.

2) The clearest path to Stage IV knowledge through the supernova technique would include a space mission with suitable spectrophotometric capability in combination with ongoing low-redshift supernova studies. DOE participation may be the only way to ensure that a space mission has the necessary spectroscopic capabilities. But given the timescale and hurdles of a space mission, there is an important near-term DOE role in exploring novel ground-based observational techniques. A DOE-led R&D program in this area could make it possible to accomplish the precision measurements for high-redshift supernovae from the Supernova Cosmology Project (SCP), DES, and LSST, complementing and strengthening these DOE projects. These ongoing low-redshift and high-redshift studies will provide major dark-energy science results over the next few years.

3) There is a need for several pilot efforts to develop the next steps of the dark-energy program. First, pilot studies, combining targeted photometric, spectroscopic, and radio observations, and informed by ongoing theoretical work, would be an opportunity to discover the information necessary to chart an effective future program in the area of modified gravity. Second, detailed studies should be carried out in the near future to determine the precise dark-energy-measurement requirements of future deep spectroscopy projects to calibrate the DES and LSST galaxy redshifts and mitigate other systematics.

I. Introduction

With the recent discovery of the Higgs boson at CERN, the final piece of the standard model of high-energy physics is in place, and the attention of many physicists turn to the search for physics beyond the standard model. The Department of Energy Office of Science has identified three frontiers to explore in the quest to discover physics beyond the standard model: The Energy Frontier, the Intensity Frontier, and the Cosmic Frontier. Two of the science thrusts of the Cosmic Frontier involve exploring the nature of dark matter and dark energy. That 95% of the present mass and energy of the universe is dark matter and dark energy is the clearest illustration that there must be physics beyond the standard model and that physics beyond the standard model is a key to understanding the composition of the universe.

The Office of Science has led the exploration of the dark universe. It supported one of the two teams that discovered that the expansion of the universe is accelerating, a discovery recognized by the 2011 Nobel Prize in Physics. The observed apparent gravitational repulsion exerted by empty space surprised the physics community, and lies on the intellectual fault line between gravity and quantum mechanics. Through observations using a variety of techniques, the Office of Science Cosmic Frontiers program has led the transformation from discovering and corroborating the accelerated expansion, to precision measurements of the effect of dark energy on the expansion. The current and approved future Office of Science program will further improve our knowledge of the nature of dark energy. But understanding dark energy involves multiple cross-cutting techniques, and a successful program to discover the nature of dark energy requires a comprehensive program, with overlapping timelines of R&D, instrument/project construction, data collection, and data analysis activities.

The acceleration of the expansion of the universe poses a deep challenge to our understanding of fundamental physics – the most prosaic explanation is that most of the energy density in the universe is in the form of vacuum energy whose density is over 100 orders of magnitude smaller than our naïve theoretical predictions. Other explanations are even more radical. Refining these measurements and further elucidating the nature of dark energy have been the focus and recommendation of numerous national reports and represents a consensus goal in the Cosmic Frontier Program.

Distinguishing competing hypotheses for dark energy requires precise measurements of the cosmic expansion history and the growth of structure. The cosmic expansion history is the observational signature most closely connected to dark energy, and indeed dark energy was first discovered by distance-redshift measurements, using supernovae, which showed the expansion rate to be accelerating.

An alternative explanation for cosmic acceleration is that gravity on cosmic scales is not described by Einstein's general relativity (GR). Such alternatives to the conventional smooth dark-energy hypothesis are referred to as modified gravity (MG) scenarios. MG theories are still being developed, but some observational implications have already emerged.

The purpose of this Report is to provide an overview of the current science reach and to identify key missing components in the current program. Augmentation of the current program with these missing components will result in significant advances in the study of dark energy over the coming years, resulting in a steady stream of important scientific results. This plan is independent of other agencies and other scientific communities, and is not facility specific.

In Section II we review the current status and future prospects of the major methods used to explore the nature of dark energy. In Section III we identify *opportunities* for the Office of Science to strengthen the program by a future wide-field spectroscopic survey and R&D in a few key neglected areas. We conclude in Section IV.

II. Methods for Studying the Nature of Dark Energy

It is now widely appreciated that no single technique or method for studying dark energy can solve the outstanding questions about the riddle of dark energy: combinations of several techniques must be used to fully realize that goal. Different techniques have different strengths and weaknesses and are sensitive in different ways to the dark energy properties and to other cosmological parameters. Combinations of the various techniques for studying dark energy described in this section decrease the uncertainties associated with systematic uncertainties. And since different techniques depend on cosmological parameters in different ways, combining techniques can greatly mitigate the associated uncertainties.

As we transition from the discovery phase to the characterization phase in dark-energy science, the challenge is to map out the history of cosmic expansion in refined detail, and to exploit these observations to establish quantitative constraints on the parameters of various dark energy hypotheses. Different ways of measuring distances (both along and across the line of sight) can be used in conjunction with redshift measurements (the integrated cosmic expansion during the photon's flight time) to map out the expansion history. Alternatively, we can exploit the fact that the growth of cosmic structure is a tension between the attractive gravitational effect of dark matter and the repulsive effects of dark energy. Moreover, by measuring the in-fall of galaxies (with precise velocity information) towards mass concentrations (seen through gravitational lensing), we can test directly our understanding of gravity on various cosmic scales. The resulting cross-braced latticework of observational constraints, drawing upon all these methods, is what will provide crucial insight into the nature of the dark energy.

The effect of dark energy on the cosmic expansion is most simply described in terms of two parameters, w_0 and w_a, where w_0 is the present value of the dark energy equation of state parameter w, and w_a parameterizes the change in w during the evolution of the universe. This simple parameterization is most useful if dark energy is important at late times and insignificant at early times. (If dark energy is due to Einstein's cosmological constant, $w_0 = -1$ and $w_a = 0$; evidence that points to other values would be a tremendous discovery.)

Currently we are in the era of what is known as "Stage III" dark-energy projects.[1] Stage III projects with and without major DOE support are listed in the first table of the Appendix. In the next section we review the Stage III progress made in the different techniques, and discuss the steps necessary to obtain the required "Stage IV" level in the different techniques.

Supernova

Type Ia supernovae (SNe) are used as calibrated standard candles to measure the luminosity distances over a wide range of redshifts, comparing nearby supernova (SN) lightcurves and spectra to those of distant SNe. The SN technique remains one of the best-proven and mature techniques for studying dark energy. The world's collection of well-measured SNe with $z < 1$ number about 700, while $z > 1$ SNe number about 25.

The Stage IV goal is to make precision measurements of Type Ia supernovae over the entire redshift range from $z \sim 0.01$ to $z \sim 2$. This requires sufficient numbers of supernovae at every redshift interval $z \sim 0.1$ such that the statistical uncertainty is below an ambitious goal of 0.5% to 1% for the systematic uncertainty in distance. Low-redshift SN programs with major DOE support are making great progress in

[1] The Report of the Dark Energy Task Force describes the various Stages and techniques.

developing the understanding of (and constraints on) the systematic uncertainties, while the planned DOE-led high-redshift SN programs (DES and LSST) will provide sufficiently large statistical samples up to $z \sim 1$. Addressing both requirements simultaneously – sufficient statistics *and* systematics control at all redshifts – presents the key remaining challenge that we discuss here. Continued work with existing or similar DOE projects can achieve this at low redshifts ($z < 0.1$), but the discovery rate of SNe is intrinsically slow at low redshift. Several more years of such surveys will be needed to yield the statistics necessary (about 500 low-redshift SNe would be needed to anchor the distance measurements and match the much larger number of high-redshift SNe).

At higher redshifts up to $z \sim 1$, DES will make great progress on the leading systematic uncertainties, and then be able to match these systematics with sufficient statistics. In particular, the relative calibration of the low-redshift and high-redshift (DES) SNe is a crucial step forward, and it would be important to have some concurrent running of the programs in these disparate redshift ranges to allow direct filter cross-calibration. Improving upon this next systematics limit for the high-redshift ($0.5 \lesssim z < 1$) SNe, however, is a definite challenge from the ground, since precision spectrophotometry is currently not possible for these large samples of very distant SNe. New approaches are now needed to replace the original space-based plan to accomplish this – and to build a matching sample above $z = 1$ – since a dedicated SN program in space now appears unlikely this decade.

Current/planned projects

The current and planned SN projects are shown in Table B in the Appendix, including their redshift ranges, and strengths and weaknesses with photometry and spectroscopy. Several trends can be seen: High-redshift ground-based SN projects that have up till now used primarily spectroscopy to obtain SN type and redshift are moving to larger and deeper primarily photometry-based samples such as will be produced by the DOE-led Dark Energy Survey (DES) and the Large Scale Synoptic Telescope (LSST) projects (with major DOE support). In their baseline plans, host galaxy redshifts (measured in large quantities long after the SN is detected) will be used instead of redshifts from SN spectra. Calibration subsamples with SN spectra will be used to constrain some SN systematics such as core-collapse contamination. Other SN systematics such as brightness correlations with host galaxies, and SN evolution with redshift, will require a community-wide effort including guidance from the DOE-led studies of low-redshift SNe. In addition, flux calibration and inter-calibration between low-redshift and high-redshift observations is a critical component of all new surveys.

There are several missing elements in the SN program that can be seen from the green regions of Table B in the Appendix. 1) The photometry needed to compare the supernovae across redshifts cannot yet be observed in the same SN-restframe wavelength ranges, as we move from low to high to very high redshift. 2) The high-signal-to-noise, calibrated host-galaxy-subtracted spectrophotometry used to constrain SN evolution in detail is so far *only* observed at low redshift – and the numbers of such supernovae are still not large enough to provide the anchor for the planned large high-redshift projects. 3) The well-calibrated restframe near-IR photometry or precision optical-wavelength color measurements that provide control for the dust-related systematics are also so far only observed at low redshift (again, with more needed). All three of these elements can be addressed by a combination of continued precision low-redshift SN work (to reach the needed sample size of at least approximately 500 low-redshift SNe), and a renewed effort to make possible the high-redshift SN measurement counterparts. Earlier DOE efforts at the high redshifts focused on a space-based program that would include spectrophotometry and IR sensitive detectors. Now, there are new efforts aimed at developing novel ground-based techniques to combine near-IR technology, suppression of the interfering bright sky lines, seeing control (e.g. adaptive optics), and sufficient time on 8-meter-class telescopes to follow up photometry survey programs such as DES and LSST.

Current status of science results

For a model where w is constant but not equal to −1, current SN plus CMB and BAO priors measure a constant w to about 6%. The corresponding constraints on time-varying DE models give an uncertainty on w_a of about 0.7. Currently the largest known uncertainty is flux calibration between low and high redshift datasets, and improving this is a focus of future surveys. SN science-related systematics, which will then become dominant, are still being studied and are also the focus of community-wide efforts to improve through observational constraints. These include brightness correlations with host galaxies, SN evolution with redshift, the interplay of SN colors and dust effects, and uncertainties in the UV flux for Type IaSNe. All of these will require guidance from large samples of well-measured low-redshift SNe.

Future results expected with current/approved program

Active programs to use HST, Subaru (and eventually JWST) to collect well-measured $z > 1$ SNe will continue to improve dark energy constraints (though with relatively small numbers of SNe). DES and Pan-STARRS will provide homogeneous samples of several thousand SNe up to redshift approximately 1, with redshift measurements provided by host galaxy follow-up. LSST will detect many hundreds of thousands of SNe in its main survey, and these could be an excellent test of dark energy isotropy. The LSST deep drilling fields measured with six filters and extremely precise photometry will provide another step forward for $z < 1$ SNe. The DOE-led SN Factory, PTF, and QUEST studies of low-redshift supernovae provide the underpinnings of all this higher redshift work: they are in the process of establishing the low-redshift anchor for the cosmological measurements while also providing the techniques needed to reduce and control the systematic uncertainties from such sources as photometry calibration, K-correction, and SN evolution.

Key Issues and Next Steps

For SNe, the important next steps are aimed at systematic error control. Progress in the DOE Dark Energy program with SNe will require careful work on several fronts:

1. Calibration instrumentation/studies, and then data collection, for the low-redshift anchor survey(s) and for the upcoming high-redshift surveys (both with major DOE support).

2. Further low-redshift survey work and analysis to identify the key SN and host features to provide systematics-control of SN evolution (and dust/color evolution) at the higher redshifts.

3. Study of the observational techniques to carry these calibration and systematics techniques to the higher/highest redshifts. This will probably require rest-frame optical and observations in the near-IR, both photometric and spectroscopic, which are difficult from the ground with present techniques. This leads to two possibilities: a space-based near-IR instrument with excellent spectroscopic capabilities, and/or a significant advancement in ground-based IR capabilities.

   a) With modest investments in spectroscopic capabilities and a small fraction of mission time, WFIRST could be upgraded to provide the detailed supernova measurements at high-redshift to match the low-redshift systematics control, especially with the possibility of using a 2.4m mirror. (WFIRST does not currently baseline this precision SN spectroscopy capability.) This would be complementary to the EUCLID program.

   b) Since such a space mission capability may not be likely to be achieved in the upcoming decade (and may require multiagency effort for the spectroscopic upgrade), there is a need to explore ground-based alternatives, combining near-IR technology with atmospheric-sky-line suppression and seeing control (e.g. adaptive optics). Sufficient time on 8-meter-class telescopes would then also be necessary to follow up photometric survey programs such as DES and LSST.

We note that these three elements together make a comprehensive DOE SN program, with a well-sequenced combination of R&D, construction, operations and analysis projects. The DOE SN researchers will be involved in several of these at any given time, since the precision SN cosmology measurement requires an in-depth understanding and use of SN data from all the redshift ranges simultaneously.

Weak Lensing

Weak gravitational lensing is the small distortion of the shapes of distant galaxies by intervening large-scale structure. Weak lensing distortions are typically of the order of 1%. Since galaxies are not all exactly round, the effect can be measured only statistically, through the correlations of galaxy ellipticities with each other (*cosmic shear*), or with the positions of foreground galaxies (*galaxy-galaxy lensing*).

Cosmic shear depends on both the distribution of matter and the distance scale of the Universe. As such it is sensitive to both the growth of structure and the expansion history of the Universe. Of particular interest is tomography – measuring the signal as a function of redshift to extract the full history of growth of cosmic structure. Galaxy-galaxy lensing depends on these but also on the (biasing) relation between galaxies and mass; for dark energy investigations it is most useful in combination with galaxy clustering observables, so that one may simultaneously solve for the cosmological and galaxy-biasing parameters.

In order to achieve competitive statistical errors, weak lensing requires deep, wide-field imaging that resolves large numbers of galaxies. The instrument point-spread function (PSF; appearance of a point source) must be extremely well characterized and its effects removed in order to avoid contaminating the very small weak-lensing signal. In addition, to interpret the signal in terms of cosmological parameters, cosmologists must know the redshift distribution of the source galaxies (typically calibrated against spectroscopic samples), and astrophysical uncertainties such as the intrinsic correlation of galaxy ellipticities and non-gravitational (baryonic) effects on the matter power spectrum must be carefully evaluated.

Recent & Current Projects

The first detections of cosmological weak lensing were relatively recent, in 2000. During the ensuing decade, a number of weak lensing programs have been carried out from ground-based telescopes and from the Hubble Space Telescope. The HST data with its exquisite angular resolution is the most valuable per unit area, but the largest of the HST surveys (COSMOS) covers only about 2 deg^2. From the ground, surveys of several hundred deg^2 have been carried out. This includes the preliminary results from the Canada France Hawaii Telescope Legacy Survey (CFHTLS). Two analyses of the deep portion of the Sloan Digital Sky Survey data (both with substantial DOE support) were released in 2011.

Current Status

To date, weak lensing results have focused mostly on the amplitude of matter fluctuations and constrained DE in combination with other cosmological probes. The error bars on recent measurements are typically about 10% (and not necessarily independent). The constraints from tomography are not yet competitive.

Several issues limit the current observational program. Statistical errors are large, and dominate over systematics in some of the more recent measurements, but only after years of work on the analysis pipelines. The most difficult challenges have been the point-spread function, its correction in the galaxy ellipticity measurement, and the avoidance of errors in data processing operations (image stacking, defect rejection, model fits, etc.). However, the contribution of other errors, e.g., the source redshift distribution and intrinsic galaxy alignments, are not negligible. Progress on all of these sources of error will be required in order to realize the potential of the Stage III surveys.

In addition to these potential pitfalls, the community will seek opportunities in upcoming Stage III surveys. Information is encoded in lensing beyond the plain vanilla power spectrum familiar from the cosmic microwave background. In particular, researchers will use a combination of theoretical research and early Stage III data to gain more information from:

- *Magnification of galaxies*, sensitive to the same structure along the line-of-sight as ellipticities and so potentially just as important in constraining dark energy
- *Non-Gaussianity*, the cosmic shear distribution is not Gaussian so information in higher-point functions might further constrain dark energy
- *Observation outside optical bandpasses,* e.g., with radio sources or the cosmic microwave background as the lensed objects instead of galaxies; indeed the first observations of the lensing of the CMB took place in 2011-12

Future Projects

The four large WL surveys to be carried out in the next five years are: Dark Energy Survey (DES; US in partnership with other countries with DOE playing a leading role), Subaru HSC (Japan), Kilo-Degree Survey (KIDS, Europe) and Pan-STARRS 1 (PS1, US and Germany). KIDS and PS1 have begun while DES and Subaru HSC expect first light within the next year. Each of these surveys cover at least 1000 deg^2 on the sky, image galaxies out to $z = 1$ and beyond, and have multi-color information to enable photometric redshift estimation. While assessment of the lensing capability of these surveys must await image quality and other diagnostics, roughly speaking, their statistical power exceeds that of the CFHTLS by more than an order of magnitude. Thus WL is probably the DE probe with the greatest expected advance in data size in the coming years. To translate into equally impressive advances in our knowledge of DE will require careful mitigation of systematic errors.

In the more distant future are the Stage IV surveys. The US-led ground-based LSST, which recently achieved DOE CD-1 and National Science Board approval for the NSF Director to request construction funding, will image essentially the entire southern sky to greater depth than any preceding ground based survey. LSST will attempt to solve out PSF-related systematics with many dither positions and multiple roll angles. An alternative strategy is to go to space to achieve a small and stable PSF, as planned for the Euclid mission (Europe). The WFIRST space mission (ranked first in the US Decadal Survey) would implement both of these strategies, but its funding remains uncertain.

Key Issues & Next Steps

The most critical issue for the weak lensing community is to improve control over the systematic errors that have been significant in the current data. Important issues to address for the upcoming surveys are:

- To the extent possible, understand the PSF and sources of variation of near-term instruments (e.g., DES and HSC) early in the projects so that this knowledge can feed into their observing strategy as well as the design of future projects. This requires integration of the lensing analysis with the actual performance of the telescope and camera at a level well beyond what has been done for Stage II surveys.

- Increase the maturity of shape measurement data analysis and processing techniques. This relies on algorithm development using both simulated and actual images of millions of galaxies. A growing fraction of this work will be specific to particular observations (e.g., detector technologies and optical layouts).

- Many "advanced" techniques for measuring, self-calibrating, or projecting out intrinsic galaxy alignments, baryonic corrections to the matter power spectrum, and uncertainties in the source redshift distribution have been suggested. More experience is needed in applying these techniques to real data. Large spectroscopic training samples are the most important additional datasets needed to calibrate redshifts and measure intrinsic alignments. Detailed studies should be carried out in the near future to determine the precise requirements for spectroscopic samples.

Clusters

The number of clusters of galaxies is sensitive to both the expansion history of the universe and the rate at which density fluctuations grow in the Universe. Since dark energy affects both the growth rate and expansion, constraints from clusters are competitive with, and complementary to, other probes.

Progress in using clusters to probe cosmology over the past decade or so has been impressive, and clusters now constrain a combination of the amplitude of fluctuations in the universe at the present time, and the amount of (dark) matter, to a few percent accuracy. Upcoming surveys, such as DES and LSST, will take the next step and constrain the growth rate, so some of the tightest constraints on dark energy are expected to come from galaxy clusters. The key systematic that stands in the way of these constraints is accurate estimation of cluster masses; this uncertainty even now dominates the error budget and will have to be addressed with multi-wavelength observations. Recently, theoretical work has shown that clusters can provide powerful tests of modified gravity models, wherein gravity behaves differently in very over-dense regions (galaxies in the centers of clusters) as opposed to more typical regions (outskirts of clusters). Similarly, a comparison of cluster masses via dual measurements of motions of cluster member galaxies and gravitational lensing can also constrain modifications to general relativity.

Current Projects

The current suite of multi-wavelength observations include: a) optical (SDSS and DES) where clusters can be identified by a variety of algorithms, and mass indicators including the number of galaxies are supplemented by direct mass measurements with weak lensing; b) microwave (South Pole Telescope, Atacama Cosmology Telescope, WMAP, Planck) where the thermal Sunyaev-Zeldovich (SZ) effect (observed intensity decrement due to CMB photons scattering off of electrons in the cluster) can be used to locate and weigh clusters; and c) X Ray (ROSAT) where the temperature (as measured with XMM or Chandra) correlates well with mass.

Current Constraints

Most constraints from clusters on dark energy utilize their number counts from observations/detections in the optical, X ray, or microwave. Typically, current cluster count measurements constrain the equation of state w to be -1 with an error of about +/-0.2 by themselves, and when combined with other (CMB+BAO+SN) data they improve overall constraints by about 30%.

In addition to constraining dark energy, cluster abundances have already been used to impose powerful constraints on modified gravity models. Optical surveys have also measured the gravitational redshift of galaxies in clusters, again placing constraints on models of modified gravity.

Future Surveys

Statistical projections suggest that clusters will provide increasingly tight constraints on dark energy and modified gravity. Improvements in the understanding of systematic errors in the observations will be necessary to realize this potential. In particular, LSST (in the optical) and ACTPol and SPTPol (in the microwave) will continue where SDSS, DES, and other surveys have left off, and find and characterize tens of thousands of clusters out to redshift of order unity. Other surveys include RCS-2, KIDS, Pan-Starrs, VIKING, Subaru (both the imaging Hyper Suprime-Cam and the complementing Prime Focus Spectrograph survey), and the space missions Euclid, eRosita, and XMM-Newton, the last two of which are dedicated European-led missions specifically targeting clusters of galaxies.

Key Issues & Next Steps

Control of systematic errors, in particular in determining cluster masses, is the most pressing challenge in using clusters as powerful probes of dark energy. To control the systematics, cosmologists will rely on multi-wavelength observations in the optical, SZ and X-ray bands. As the physics of galaxy clusters is better understood and new observations become available, it is expected that clusters will become powerful probes of dark energy in two particular respects: measuring the growth of density fluctuations (in addition to expansion history), and testing theories of modified gravity through observations of individual clusters as well as their population as a whole. Spectroscopic surveys would allow for measurements of velocity dispersions, which would help estimate cluster masses. Overall, spectroscopic surveys would contribute significantly to calibrating cluster observables, helping to address the fundamental challenge that now stands in the way of clusters becoming a powerful, reliable probe of dark energy and modified gravity.

Baryon Acoustic Oscillations/Redshift-Space Distortions

The three-dimensional spatial and velocity distribution of galaxies, most commonly characterized by its two-point correlation function or power spectrum, is a powerful probe of dark energy and modified gravity. The two methods that use this information are the Baryon Acoustic Oscillation (BAO) and Redshift Space Distortion (RSD) methods which constrain both the expansion history and growth of structure.

The BAO method uses the apparent size of a standard ruler to measure the expansion history of the Universe, and is therefore, like supernovae, a geometrical probe of dark energy. The BAO standard ruler is a characteristic feature in the matter distribution of the Universe, imprinted when sound waves in the early plasma of the Universe get frozen in as the Universe cools. This standard ruler is usually described as an excess probability for pairs of galaxies to be separated by approximately 150 Mpc, or about 500 million light years. Measuring the apparent size of this ruler constrains both the angular diameter distance and the Hubble parameter, providing complementary information to supernova measurements.

The RSD method is a dynamical probe of dark energy. The distribution of galaxies is expected to be statistically isotropic. However, since the distances to galaxies are measured through redshifts (velocities), this isotropy is destroyed by galaxy motions towards and away from us. The RSD method uses this anisotropy to (statistically) measure the velocities of galaxies and therefore measure the growth rate of structures in the Universe. This in turn provides dynamical measurement of the effects of dark energy. Furthermore, in General Relativity, the expansion history predicts the growth of structures (and vice versa). The combination of the BAO and RSD techniques can therefore additionally test for modifications to General Relativity on cosmological scales.

Both the BAO and RSD methods are made possible by large spectroscopic galaxy surveys; indeed, most (and the most precise) measurements have been made using such surveys. While new methods (e.g., 21cm intensity mapping) may create further opportunities, spectroscopic surveys will remain the most versatile and mature approach for the near future. Furthermore, the BAO and RSD methods have similar requirements allowing projects simultaneously to optimize for both.

Current Surveys

The BAO method was first demonstrated in 2005 using the Sloan Digital Sky Survey (SDSS) and Two Degree Field galaxy surveys. Recent re-analyses of the completed SDSS data have yielded a distance precision of 2% at a redshift of 0.35.

There are currently two ongoing or recently completed BAO/RSD surveys. The first (and now completed) is the WiggleZ survey using the AAT telescope in Australia, which covered approximately 1000 deg^2 on the sky, measuring redshifts to 200,000 galaxies below a redshift of 1 (with a median redshift of 0.6). WiggleZ has published its first BAO and RSD analyses, with a 4% distance measurement at an effective redshift of $z = 0.6$ and a measurement of the growth rate of 10% in four redshift bins between $z = 0$ and 1.

The Baryon Oscillation Spectroscopic Survey (BOSS), funded in part by DOE, aims to make 1% distance measurements at $z = 0.35$ and $z = 0.6$ using galaxies, and a 1.5% distance measurement at $z = 2.5$ using the Lyman-alpha forest. The Lyman-alpha forest measurement will be the first detection of the BAO feature using a tracer other than galaxies. Early results from BOSS detected the 3D clustering in the Lyman-alpha forest for the first time, and the first Lyman-alpha BAO results from BOSS are expected by the end of 2012. BOSS started taking data in 2009, and will be complete in 2014. When complete, it will have surveyed 1.5 million galaxies and 160,000 quasars over 10,000 deg^2 of the sky. The first cosmological results from the BOSS galaxy survey were released in April, 2012 resulting in a 1.7% distance measurement (currently the most precise distance measurement from a BAO survey) and a 7% measurement of the growth rate, both at a redshift of 0.57.

Future Surveys

The HETDEX survey will map the distribution of galaxies between redshifts 2 to 4. The survey is expected to begin in 2014 and is expected to take data for three years, surveying a region of approximately 500 deg^2 and obtaining a 1% distance measurement at $z = 3$.

The bulk of the cosmological information is encoded in the 3D clustering of galaxies. Wideband photometric surveys like DES and LSST can, in principle, measure BAO using photometric redshifts to get coarse 3*D* information. However, the relative inaccuracy of photometric redshifts smears out this 3D clustering and significantly reduces the precision with which cosmological parameters can be measured. Therefore, photometric measurements of BAO, while certainly possible, are not competitive with spectroscopic surveys. For very similar reasons it is also impossible to perform RSD measurements from photometric data. These disadvantages may be partially mitigated by narrow-band photometric surveys, like the PAU (Physics of Accelerating Universe) and J-PAS projects. While these approaches may prove to be interesting alternatives, they are currently unproven and lack the maturity of spectroscopic surveys. Similar conclusions are true for 21cm intensity mapping experiments like the CHIME project.

In the more distant future, the Euclid satellite, scheduled to launch in 2019, will perform a BAO/RSD survey between redshifts of 0.7 to 2.0, yielding Stage IV level constraints over this redshift range. The unique capability of such a space based mission is a galaxy survey above redshifts of 1.5, where the atmospheric backgrounds make ground-based surveys prohibitive.

Key Issues & Next Steps

The BAO method has proven to be a particularly robust method of measuring the expansion history of the universe, because the vast majority of systematic effects, both astrophysical such as non-linear scale-dependence of the bias or systematic (non-uniform survey depth, redshift-failures, etc.) are ignorant of the characteristic BAO scale and produce broadband corrections to the two-point function that can be marginalized out without loss of information. While nonlinear evolution and galaxy bias are expected to have measurable effects for future surveys, it is widely expected that these can be calibrated by a combination of analytic and numerical techniques. However, the very large scale of the BAO feature places a fundamental limit on the statistical precision possible.

Redshift-space distortions are observationally as mature as BAO, as the observations required are very similar in spirit to the BAO (taking spectra of objects and measuring the two-point statistics of the tracer's fluctuations). The precise parameters (number density, depth, etc.) could in principle be optimized for one or the other technique, but are generically similar. Theoretically, however, it is unclear how much information can robustly be recovered from the observed correlation function or power spectrum. The theory is well understood on the largest linear scales, and this sets the lower, most conservative limit on how well one could do. However, it is believed that better theoretical understanding of intermediate scales, where gravity is weakly non-linear and galaxy bias weakly scale-dependent will inevitably happen on the timescale of proposed projects. This will likely be achieved through a combination of large number of big cosmological simulations and further analytic insights. The uncertainty about how well the theory will be developed in the next decade makes it very hard to robustly forecast the ability of RSD to constrain cosmology. Even in the conservative scenario, the method is still powerful, but in the best case it could become one of the premier methods of observational cosmology.

The BAO/RSD techniques have matured remarkably in recent years, demonstrating their statistical power and control of systematic errors. The next step for these techniques is to push the current precision measurements to higher redshifts. A key missing ingredient in the US program is a near-term Stage IV level BAO/RSD spectroscopic survey at redshifts greater than the redshifts probed in Stage III projects. This could be competitive with and earlier than the Euclid measurements and build off the experience gained from ongoing experiments. Such a survey would obtain spectra for an order of magnitude more galaxies than any existing survey. This would require new automated wide-field and massively multiplexed spectroscopic instrumentation but could effectively use existing telescope facilities.

III. Opportunities for the DOE Dark Energy Program

The LSST project has received DOE CD-1 approval as well as approval by the National Science Board of the NSF for the NSF Director to seek construction funds. The LSST photometric survey will be a Stage IV Dark Energy Project that greatly advances our knowledge of the nature of dark energy, in particular, through the method of weak lensing. LSST will also provide some information about dark energy through the BAO, SN, and Clusters methods.

But there are two crucial missing ingredients necessary to understand the nature of dark energy by reaching full Stage IV levels for the other methods: a Stage IV wide-field spectroscopic survey and a program that results in Stage IV supernova measurements.

Stage IV Wide-Field Spectroscopic Survey

A crucial missing ingredient of a cross-cutting DOE dark-energy program is a future wide-field spectroscopic survey that would provide Stage IV level BAO/RSD. It would also provide calibration data and other information that will be used to improve dark-energy constraints from photometric surveys like DES and LSST. Galaxy spectra would allow for 3-*D* mapping of the baryon acoustic oscillations set up in the early universe and would uncover the anisotropies in the clustering of galaxies, so-called *redshift space distortions*. The former leads to a localized measurement of the Hubble expansion rate at the redshift of the galaxies (as opposed to distance measurements, which are sensitive to an integral of the expansion rate out to that redshift) and provides additional defense against observational systematic errors. Using this technique, future wide-field spectroscopic surveys would be able to constrain the expansion rate at the percent level out to redshifts well above those probed by current Stage III projects, significantly improving upon current constraints. A survey with redshift space distortions (RSD) is a particularly powerful probe of the growth of structure. Such a survey therefore would increase the dark energy figure of merit and help distinguish modified gravity from dark energy. Indeed RSDs are among the most powerful ways of addressing whether the acceleration is caused by dark energy or modified gravity. The discrimination becomes all the more powerful when redshift surveys are combined with weak-lensing observations. A *wide-field* spectroscopic survey is necessary to reach systematic limits.

Along with these two major advantages, spectroscopic surveys have the power to reduce systematics in the clusters and weak-lensing probes. Perhaps most importantly, a spectroscopic survey is instrumental in calibrating photometric redshifts upon which DE probes in all photometric surveys rely to some degree. This feeds directly into more precise measurements of dark energy from lensing and large-scale structure. The benefit for clusters, in terms of photometric redshift calibration, is particularly large if precise redshifts of brightest cluster members can be obtained. Further spectroscopy of multiple cluster members could be used to measure velocity dispersions, which contain additional information about the mass calibration so central to cluster cosmology. The spectroscopic measurements can also ameliorate both observational and astrophysical systematic effects in imaging surveys.

We cannot judge whether a single spectroscopic survey will provide all the necessary information. There are many considerations in the optimization of a spectroscopic survey. A single spectroscopic survey operation mode may not be able to do everything discussed above, but if properly optimized it will still make a significant impact through the combination of intrinsic cosmological measurements and systematic error mitigation. We emphasize that the precise specifications of such a survey -- including its location -- are beyond the scope of this report.

A DOE-led Stage IV spectroscopic survey would build on the experience of ongoing DOE projects (*e.g.,* BOSS) and would continue DOE leadership in this area into the next decade.

Stage IV Supernova Measurements

Several key ingredients will allow the DOE program to build on the photometric survey projects (DES and LSST) so that Stage IV supernova measurements of dark energy can be accomplished. First, the low-redshift searches (e.g., PTF, QUEST), follow-up (e.g., SN Factory), and data analysis projects will continue to build the foundational measurements – the crucial knowledge to identify and constrain systematics, and the low-redshift statistical sample large enough to compare with the planned high-redshift datasets.

A future Stage IV space-based SNe project would be the simplest way to match, at high redshift, these precision measurements of Type Ia supernovae at low redshift – measurements needed to provide the same systematics control over the entire redshift range from $z \sim 0.01$ to $z \sim 2$. With modest investments in spectroscopic capabilities and a small fraction of mission time, WFIRST could be upgraded to become this project, and would be complementary to the lensing programs of LSST/EUCLID. However, given the timescales and many difficulties of a space mission, there is now a need to explore vigorously a ground-based alternative to fill this important missing element in the DOE program. In particular, an

R&D effort to explore the potential of novel ground-based techniques, combining near-IR technology with OH sky-line suppression, could make it possible to accomplish the precision measurements for SNe from SCP, DES, and LSST, complementing and strengthening these currently approved DOE projects.

In addition to the above two key missing ingredients, a forward-looking dark energy program should include studies to generate new ideas for the future. We identify two promising areas where there is the opportunity for modest pilot studies to have a large impact in the future direction of dark-energy studies. These pilot studies are in the areas of modified gravity studies and studies of future deep spectroscopy projects to calibrate the DES and LSST galaxy redshifts.

Pilot Studies to Develop a Future Modified Gravity Research Program

Modified gravity models will be tested by upcoming surveys such as DES and LSST, and also with a spectroscopic survey that uses redshift space distortions in conjunction with weak lensing. The last several years have seen a burgeoning of ideas of new tests beyond those possible with traditional galaxy surveys. In addition to large-scale tests that fit in naturally with the dark-energy program, a new regime of gravity tests is available following from the observation that modified-gravity models must reduce to standard gravity in the solar system. The proposed tests then exploit the transition from modified gravity on large scales to standard gravity on much smaller scales. Understanding precisely how to probe this transition is still an active area of theoretical research, with candidate observations ranging from pulsating stars to the warps and motions of nearby galaxies. Pilot studies, combining theory and targeted observations, would help chart an effective future program, for instance, a combination of lensing and dynamics, via imaging and spectroscopic surveys over a range of scales comparing halo masses of individual galaxies and clusters, or larger scale structures that induce coherent infall motions of galaxies.

Pilot Study to Develop a Program for Spectroscopic Calibration of Wide-Field Photometric Surveys

Spectroscopic surveys are crucial to properly calibrate photometric redshifts for the next generations of wide-field photometric surveys. The next generation surveys, in particular LSST, will require deep spectroscopic data.

Detailed pilot studies should be carried out in the near future to determine the precise dark-energy measurement requirements of future deep spectroscopy projects to calibrate the DES and LSST galaxy redshifts.

IV. Conclusion

The effort to understand the nature of dark energy remains at the forefront of the interface between high-energy physics and astrophysics, and is a central component of the Office of Science Cosmic Frontier program. Historically, the DOE has led in the exploration of this area of the cosmic frontier, supporting one of the two teams that announced the acceleration of the expansion of the universe, a discovery that was recognized by the 2011 Nobel Prize in Physics.

The next few years will see a tremendous influx of new results from the DOE dark-energy program. But currently operating projects (including DES, scheduled to commence operations in November of 2012) are scheduled to end in 2018, and results from LSST will not be forthcoming until early in the next decade.

LSST will provide Stage IV information about dark energy through the technique of weak lensing and will also provide some information about dark energy through the other methods. But the Cosmic Frontier community recognizes that to reach full Stage IV levels for the other methods, and to optimize the vast amount of information from LSST, other complementary information will be needed. Since no single technique or method for studying dark energy can resolve the outstanding questions about the riddle of dark energy, a cross-cutting dark-energy program is required.

In this Report we identified key missing elements of the DOE dark-energy program. These include a spectroscopic survey, which would provide Stage IV level BAO/RSD measurements and provide calibration data and other information that will be used to improve dark-energy constraints from photometric surveys like DES and LSST. A spectroscopic survey would produce important dark energy science results in the period between the completion of the Stage III DES photometric project and the arrival of results from the Stage IV LSST photometric project.

To advance the SN method to Stage IV level, continued low-z supernova studies are needed, coupled with an R&D program to explore innovative ways to study high-z supernovae from the ground, and continued exploration of DOE participation in the study of supernovae from space.

Finally, we note the opportunity for pilot studies are in the areas of modified gravity studies and studies of future deep spectroscopy projects to calibrate the DES and LSST galaxy redshifts.

Appendix A. Current Dark Energy Projects

Approved ongoing & future dark-energy projects with major DOE support.

Status	Method	Name of Project	Comments
Current (Stage III)	BAO/RSD	BOSS	Through 2014
	SN	SCP	$z > 1$ surveys 2014-17
	SN	SN Factory	Continued through about 2018 to reach needed sample of approx. 500 nearby SNe.
	SN	Palomar Transit Factory	
	SN	QUEST	
	WL, SN, Clusters, BAO	DES	Late 2012-2018
Planned (Stage IV)	WL, SN, Clusters, BAO	LSST	CD-1 (DOE)

Proposed & possible future cosmology projects potentially with major DOE support

Status	Method	Name of Project	Comments
Future	BAO/RSD	eBOSS	Follow-on to BOSS
	BAO/RSD	BigBOSS	Proposed for Kitt Peak
	BAO/RSD	DESpec	Proposed for CTIO

Ongoing and upcoming cosmology projects without major DOE project support.[1]

Location	Survey Type	Name of Project	Comments
US	Spectroscopic	HETDEX	BAO
	Imaging	PS1, SkyMapper	SNe primary probe
	Space	WFIRST*	NASA, DOE scientist support
	Millimeter	ACTpol, SPTpol (SZ)	Clusters NSF/some DOE
	21cm	BAOBAB[2], PAPER, MWA	Signal detection is initial goal, dark energy in future
Non-US	Spectroscopic	Subaru PFS (Japan+), PAU, JPAS (Spain+), 4MOST[2] (Europe)	BAO primary method
	Imaging	KIDS (Europe), Subaru HSC (Japan+)	WL is the primary probe
	Space	Euclid (Europe)	DOE scientist support
	21cm	CHIME[2] (Canada+)	Other projects planned, but not for dark energy
	Space	eROSITA (Germany+)	Galaxy Clusters via X ray

[1] The primary science goal of some of these projects is not dark energy.
[2] Project (that to our knowledge) has yet to obtain substantial funding.

Appendix B. Parameters of current and future supernovae data sets referred to in the supernovae part of Section II.

All numbers and ratings are very approximate

Measurement Coverage Scale: **emphasis of project** … **not a goal of project**
(both in terms of quality and completeness for all SNe in sample)

* = DOE funding (full or partial)

	Redshift Range			Photometry					Spectroscopy		
						Mulitband Lightcurves					
	Lowest Redshift	Highest Redshift	# SNe usable for cosmology	Photo-Redshifts	High-precison Calibration	Restframe UV	Restframe Optical	Restframe Near-IR	Spectro-Redshift	SN-typing Spctroscpy at max	High S/N, Multi-date Spectro-photometry
Low-Redshift											
Current/Ongoing											
CSP	0.001	0.06	25								
CfA	0.001	0.06	80								
* SN Factory	0.01	0.08	220								
* PTF + followup	0.005	0.15	150								
* Quest + followup	0.005	0.15	?	?	?	?					?
Planned/Future											
PTF-II + followup	0.005	0.15	?								
Medium-High Redshift											
Completing											
* SDSS	0.05	0.4	250								
Essence	0.2	0.8	200								
* SNLS (SCP)	0.2	0.8	500								
Current/Ongoing											
Pan-STARRS	0.05	0.9	400								
* DES + followup	0.2	1	4000								
* DES + intensive subsamples	0.2	0.4	400								
Planned/Future											
* LSST	0.2	1	50000								
Very High Redshift											
Current/Ongoing											
HST field search	0.9	2	8								
* HST cluster search (SCP)	1	1.8	10								
Planned/Future											
Euclid, if SN program exits	0.8	2	1000								
Subaru HyperSuprimeCam + follo	0.9	1.5	30								
WFIRST	0.3	2	1000	?		?		?	?		?
Primary Systematics Addressed:					Cross-redshift calibration	SN evolution	SN evolution, Dust	Dust, SN evolution		Non-SN Ia contamina-tion	K correction, SN evolution, Dust