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Dark Energy and Cosmic Acceleration in the Modern Universe

4.1 Executive Summary

Despite tremendous advances over the past 20 years in our understanding of the cosmological model thanks to the continuing development of new instrumentation and experimental techniques, fundamental questions remain open. What is the nature of Dark Energy? Is general relativity the correct theory of gravity at all scales and at all times? What is dark matter and how does it connect to the standard model of particle physics? What can we learn about how inflation established the initial conditions for the Universe as we observe it today? Data from the modern universe following the epoch of reionization ($z < 6$) have played a key role in our attempts to answer these questions, and should continue to do so in the coming decades.

Some opportunities to make progress emerge directly from these major theoretically motivated questions, while others are driven by unexpected tensions between cosmological datasets. The values obtained for the rate of cosmic expansion today (as measured by the Hubble parameter) and the amplitude of matter density fluctuations each differ if one infers them from low-redshift data alone or anchors them at the cosmic microwave background at $z \sim 1100$. These tensions have become uncomfortably large, but cannot be satisfactorily explained using the most natural extensions of the standard cosmological model with new physics.

These questions and anomalies can be most effectively addressed in the coming years by a multi-probe experimental approach, spanning a variety of methods and price points to provide a rich, deep, and flexible portfolio which will simultaneously constrain both possible explanations for cosmic acceleration and a wide variety of physics beyond that area. Community input has identified a variety of key opportunities to advance our knowledge.

The most powerful opportunities would be enabled by a new, Stage V spectroscopic facility, requiring implementation of a highly-multiplexed spectrograph on a new, large-aperture ($\gtrsim$6 m), wide-field-of view telescope. Proposals for such a facility include the Maunakea Spectroscopic Explorer, MegaMapper, and European Southern Observatory SpecTel concepts. Such a facility would enable two different promising directions for experiments to be undertaken simultaneously, while also obtaining data that could constrain models of dark matter:

- **Lower-redshift ($z < 1.5$), high-density spectroscopic surveys tracing non-linear scales:** Dramatically increasing the number of galaxies with z measurements at lower redshift will provide datasets that are highly sensitive to minute departures from the standard model of gravity and dark matter, while providing multiple cross-checks that will make results robust to systematic effects. To interpret data from these experiments optimally, additional investment in simulation and theory work will also be needed.
- **High-redshift ($z \gtrsim 2$), high-volume spectroscopic surveys tracing linear scales:** A next-generation high-redshift survey could sample large volumes beyond redshift of $z > 2$ to maximize

the number of well-measured *linear* modes. This will enable extremely sensitive measurements of early universe physics, including providing tests for primordial non-Gaussianity and features in the matter power spectrum as well as constraints on early dark-energy models.

The combination of low-redshift and high-redshift surveys will enable direct measurements of the cosmic expansion history throughout the modern universe; each will also constrain basic cosmological parameters including the radiation energy density and masses of neutrinos. In the absence of a Stage V spectroscopic facility, more limited versions of one of these surveys could be undertaken or prototype exploration of both strategies could be done using the existing DESI instrument.

In addition to the science opportunities enabled by large surveys on a new spectroscopic facility, the community has identified other promising areas for future work:

- **Enhancing the science gains from near-future facilities:**
  The science return from upcoming experiments, particularly the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST), can be greatly enhanced with modest investment into follow-up observations, including roles for small-aperture telescopes, large telescopes, and the upcoming generation of Extremely Large Telescopes. *Photometric redshifts* will likely constitute the limiting systematic for LSST; their performance can be enhanced and systematics mitigated via dedicated calibration surveys executed on existing instruments and/or a Stage V spectroscopic facility, greatly improving the cosmological constraining power of LSST data. *Supernova cosmology* requires the use of follow-up facilities, both in a time-sensitive manner to accurately determine the classifications for a subset of LSST supernovae as well as non-time-sensitive redshifting of supernova host galaxies. *Strong lensing cosmology* requires follow-up imaging to measure quasar light-curves in LSST-identified systems, high-priority observations of any strongly-lensed SN candidates, and adaptive optics IFU spectroscopy to measure source positions and lens galaxy velocity dispersions. *Peculiar velocities of low-redshift Supernovae* provide a novel tool for measuring the structure of the universe at the lowest redshifts, but requires assembling data from a network of modestly-sized telescopes to measure precision light-curves and measure spectra of those objects. *Future use of the Vera Rubin Observatory after completion of LSST* should be evaluated in a dedicated exercise later in this decade once the performance of LSST and the progress of other projects is known. Options include new surveys with a different focus (cadence, area, depth, etc.), modest instrumentation changes such as a new filter set, or more radical alterations to the system.
- **Research and development to enable future probes of cosmology:**
  There a number of areas where investment now could enable novel and potentially powerful cosmological probes to begin operations in future decades. *High-precision optical spectroscopy* techniques are being developed that would enable direct measurements of the expansion rate of the universe in the next few decades. *High-precision astrometry* methods are also now being developed that would enable novel dark matter and cosmological probes by observing the evolution of the universe in real time. Some of these techniques include novel uses of quantum measurement methods that are being explored and funded in other contexts. *21 cm Spectroscopy and Line Intensity Mapping* are novel techniques that have the potential to transform our ability to measure large-scale structures in the universe by observing the aggregate fluctuations in intensity rather than individual objects, but require further investments to become competitive.

The modern universe is rich in cosmological information, providing many opportunities to improve our understanding of fundamental physics, including exploring the nature of cosmic acceleration but extending far beyond.

4.2 Introduction: Key Physics Questions and Opportunities

Our understanding of cosmology underwent a phase transition in the early 2000s, when the experimental data became good enough to move from order of magnitude estimates for many fundamental cosmological parameters to ten percent level constraints. At this time, ΛCDM emerged as the standard cosmological model. ΛCDM contains only a handful of fundamental parameters, yet has proven to be generally consistent with a large compendium of experimental data. Measurements advanced rapidly at that time: statistical uncertainties halved with every generation of experiments, while at the same time remaining large enough that only the largest and most obvious systematic errors were important.

Over the next decade, in the 2010s, the community coalesced around larger experiments and collaborations in order to make progress, much as has happened in other areas of high energy physics. New, more complex datasets have required processing by sophisticated codes developed by teams comprised of many individuals. Our ability to constrain cosmological models has continued to grow rapidly; today we know the value of many cosmological parameters with a one percent level precision.

Yet, many key open questions about our universe remain unresolved:

- *What is dark matter?* While the constraints on deviations from a cold, interaction-less fluid have improved by orders of magnitude, we have not yet found a smoking gun of what new physics is responsible for the presence of dark matter and what fundamental physics governs its microscopic properties.
- *What is dark energy?* By the early 2000s, it was clear that some unknown component must drive the accelerating expansion of the universe (assuming that general relativity is the correct description of gravity); today, we know that this component must have an equation of state that matches that of a vacuum energy at the few percent level. However, the space of theories that are consistent with observations remains large.
- *What is the nature of cosmic inflation?* It is still unknown if inflation left observable footprints that will help us to discern details of its mechanism. Through stringent upper limits on the amplitude of the primordial gravitational waves, we know that the simplest inflationary models (consisting of scalar field with a quadratic potential) are ruled out. Future observations of inflationary relics in the density fields observed by next-generation spectroscopic surveys could transform our understanding of the Universe.
- *Is gravity well-described by Einstein's general relativity, or do we need new degrees of freedom to describe its action on cosmic scales?* General Relativity (including the mysterious components of dark matter and dark energy) can describe observed phenomena over 30 orders of magnitude in distance scale, ranging from sub-millimeter force measurements in the laboratory to the largest observable scales in the Universe. Yet, we still hope to find new aspects of the theory that will allow us to ultimately connect it to the standard model of particle physics. Modifications to general relativity could offer an alternative explanation for the observed cosmic acceleration.

There are tantalizing hints of new physics in the observations that we have. Measurements made at early and late times in the history of the Universe do not seem to agree perfectly. The present-day cosmic expansion rate inferred from observations of CMB combined with lower-redshift probes is a few percent lower that that inferred via the direct distance ladder; the statistical significance of this difference in some cases exceeds 5σ. Similarly, the amplitude of cosmic density fluctuations inferred from weak lensing and other probes at lower redshift is low compared to extrapolations from the high-redshift universe. While the tension in these measurements is less strong, its statistical significance is getting uncomfortably high.

These tensions did not appear in sectors where we expect them to appear and they do not have a natural explanation; i.e., we have not yet found a convincing theoretical explanation that would allow us to convert a 5σ tension directly into a 5σ detection of a new phenomenon. They point towards new, promising, research directions that build on the techniques developed to study cosmic acceleration in the modern universe, which we describe in this chapter. If these tensions are real, they will provide a wonderful opportunity to learn something fundamentally new.

Many cosmological techniques proposed during the 2000s have now borne fruit; for example, weak gravitational lensing was identified as the method of choice for constraining Dark Energy in the 2005 report of the Dark Energy Task Force [1], but only became truly competitive after 2015 (REF needed). Baryon Acoustic Oscillation (BAO) measurements have delivered spectacular results with minimal systematics, but are also beginning to exhaust their potential at the lowest redshifts ($z < 0.5$) where existing samples cover significant portions of the available volume. Today, intensity mapping using the 21 cm hydrogen line has nominally a very high potential statistical signal-to-noise at redshifts that are only poorly sampled by other methods, but current generation of technology demonstrators are plagued by phase calibration and foreground uncertainties.

A clear lesson from this recent history is that the experimental frontier needs to be advanced via multiple avenues, rather than focusing on only one potential area of advance. Different techniques of constraining cosmic acceleration and related phenomena are highly complementary, and combining them often enables strategies to mitigate certain types of systematic errors. An experimental program that is broad along multiple axes, including the wavelengths used for observations, cosmological length-scales, redshift ranges, as well as price points, is our best bet for discovering new physics. Given the rich datasets future experiments could provide, the opportunities for discovery extend far beyond constraining the source of cosmic acceleration.

As experiments have continued to obtain richer datasets, we have found new and exciting ways of extracting information from them. For example, the original Sloan Digital Sky Survey (SDSS) was not designed to measure baryonic acoustic oscillations, and yet their first detection was one of the key discoveries from it [2]. A more recent example is the BOSS experiment, which was never designed to measure BAO in the cross-correlation between Lyman-α forest and quasars; yet this cross-correlation yields the highest precision BAO measurement to date [3]. The inverse distance ladder method of extrapolating the value of the Hubble parameter from high to low redshift while utilizing very few assumptions [4] was another novel combination of cosmological data that has led to one of the most interesting cosmological tensions today [5]. Many similar examples can be found in other experiments.

While we cannot forecast what novel techniques will be applied to the new, rich datasets from the proposed experiments described in this report, those experiments should also provide a wide variety of guaranteed measurements that will have impact on the wider physics community. They are being designed to measure the BAO distance scale, redshift-space distortions (which provide tests of general relativity), and the matter power spectrum in new regimes that have not yet been explored, but the expected gains go far beyond that. A prime example is measurements of total mass of all neutrinos. The current generation of cosmic experiments has already ruled out the inverse hierarchy, while the upcoming generation is expected to reach a neutrino mass detection at several sigma significance, even if the neutrino mass is at the lowest value consistent with neutrino oscillation experiments. The upcoming generation should bring these measurements to exquisite precision.

Multi-purpose datasets should be particularly valuable given that experiments have not yielded an unambiguous path forward for resolving the nature of cosmic acceleration. The situation is in some ways reminiscent of that in the high energy physics: a major motivation for the ATLAS and CMS experiments at LHC was to discover and characterize the Higgs particle. However, now that its mass has been measured and its properties found to be compatible with the simplest consistent model, the next steps to take are more ambiguous.

Community input via the Snowmass process has largely focused on two complementary approaches on how to move forward, each of which will address the key physics opportunities described above. Pursuing a combination of both of these strategies simultaneously, as proposed Stage V spectroscopic facilities[1] would enable, is currently the most promising route forward.

Lower-redshift ($z < 1.5$), high-density spectroscopic surveys tracing non-linear scales: The first promising approach is to continue to focus on the era when the expansion of the universe began accelerating ($z \lesssim 1$) by obtaining redshifts for much larger samples of galaxies, in order to take advantage of the large amount of cosmological information available on smaller scales at which overdensities grow non-linearly [6]. It is much easier to measure redshifts for lower-z galaxies than their higher redshift counterparts, as such objects are both brighter and easier to pre-select. Given a fixed investment in instrumentation and observing time, one can typically measure redshifts for an order of magnitude more galaxies at $z \sim 0.5$ compared to $z \sim 4$. Proposed spectroscopic facilities would be capable of measuring spectra for hundreds of millions of galaxies in this redshift range.

The dense sampling from such a survey would provide a high-fidelity map of the cosmic web of large-scale structure, enabling many rich statistical measurements of its properties. The main difficulty posed is one of interpretation: methods for constraining cosmological parameters from the smaller-scale, non-linear density field are still in their infancy and would need further support to be developed in full. However, given the rich information content of cosmic structure at small scales, it is very intuitive to expect that such a dataset would be correspondingly rich in science opportunities, including ideas that have not yet been developed. For example, explanations of cosmic acceleration that rely on modified gravity may leave distinct imprints in the cosmic web that would only be detectable in such high-fidelity measurements.

High-redshift ($z > 2$), high-volume spectroscopic surveys tracing linear scales: The second approach is to focus on improving measurements of the large-scale structure traced by galaxies on large, linear scales [7], but to expand samples at higher redshifts. Galaxy survey observations at these scales have been a key tool for constraining cosmology for two reasons. First, we can model the largest scales precisely using effective field theory (EFT) models that have well-understood convergence properties and nuisance parameters. Second, the largest-scale modes that evolve only linearly retain imprints of early conditions in the universe, allowing the physics of inflation to be explored.

A series of spectroscopic survey experiments have sampled large volumes with sufficient number density to measure structure on large, linear scales, including the Sloan Digital Sky Survey (SDSS) I and II, the BOSS experiment conducted as part of SDSS-III, the eBOSS survey component of SDSS-IV, and now the dedicated DESI experiment subsection 4.3.2. These surveys have measured the Baryon Acoustic Oscillation distance scale and thereby constrained the cosmic expansion history over a large range of redshifts, spanning the transition from the matter-dominated to the dark energy-dominated era (REF needed). EFT approaches have been used to measure cosmological parameters from these surveys (REF needed). The datasets have also been used to test for primordial non-Gaussianity and other inflationary relics (REF).

The natural extension of these methods is to apply them at higher redshifts. Extending the redshift reach of linear mode probes to span from $z \sim 2$ to $z \sim 6$ would quadruple the available volume compared to current surveys, while also probing a time when the universe was younger and dark matter overdensities were more linear and hence could retain a clearer memory of their initial conditions. The resulting datasets can be used to explore numerous topics in cosmology, including the expansion history at redshifts before dark energy domination (potentially constraining early dark energy models), neutrino masses, the radiation content of

[1] following the Dark Energy Task Force standard for defining stages for classifying dark energy experiments [1]

the Universe, tests for primordial non-Gaussianity and for features in the primordial power spectrum, and beyond [7].

These two ideas should form the backbone of future flagship experimental efforts if we are to continue to advance our understanding of cosmic acceleration and related phenomena. However, a balanced cosmological program should have a roughly pyramidal structure with a multitude of projects at different price points. In addition to the new, large redshift samples that a Stage V spectroscopic facility would enable, the community has identified two other broad routes towards enriching the progress of cosmology research in the next decade via studies of the moderate-redshift Universe.

Enhancing the science gains from near-future facilities: First, there are great opportunities to improve the cosmological constraining power from current and near-future experiments via targeted efforts that are relatively modest in scale, as described in [8]. Many of the potential gains would come from obtaining additional data to complement measurements from the Rubin Observatory Legacy Survey of Space and Time (LSST), which will provide the premier wide-area photometric dataset at optical wavelengths for the foreseeable future. Photometric redshifts are likely to be the limiting source of systematic errors for LSST cosmology studies; as a result, improving photo-z's by obtaining deep spectroscopic training and calibration datasets is an obvious opportunity for improvement.

Additional data could also greatly enhance LSST supernova and strong lensing science by enabling better photometric light curve measurements, providing spectroscopic confirmation of supernova types and lensing system candidates, or measuring redshifts of host galaxies (which can still be done after a supernova fades). There are also a variety of science opportunities that can be pursued using the Rubin Observatory after the completion of the main LSST survey, as described in [9]. These could include new surveys with different focus (cadence, area, etc.) using an unchanged LSST camera or could involve modest changes to instrumentation (for example, by changing filter sets).

Developing precision methods for future probes of cosmology: Additionally, there are a number of emerging new technologies that might enable precision measurements of fundamental physical observables such as redshifts and astrometric positions. These technologies are in their infancy and are not yet ready for deployment. However, investing in them now is important in order to enable future transformational experiments in cosmology. As one example, spectrographs with massively increased wavelength accuracy would enable direct measurements of cosmic expansion as well as a several-fold increase in limits on the variation of fundamental constants. Similarly, highly-precise astrometry will also enable new probes; e.g., extremely accurate measurements of 3D motions of stars in and around our Galaxy can be used to constrain properties of dark matter and models of modified gravity through near-field cosmology. In the future, massive surveys of proper motions of extragalactic object might even enable direct statistical measurements of proper motions of galaxies in correlation with other tracers of structure.

In the remainder of this report, we explore the opportunities to improve our understanding of cosmic acceleration and the modern universe in more detail, building upon the input provided by the community. In Section 4.3 we describe the current state of surveys of the modern universe, including experiments whose analysis is still underway or which will soon begin taking data. Section 4.4 presents the science opportunities that would be enabled by massively-multiplexed spectroscopic capabilities, including a potential Stage V spectroscopic facility as well as the possibility of continuing observations with DESI. In Section 4.5 we describe science opportunities that would be enabled by small investments to complement near-future facilities; Section 4.6 focuses specifically on those measurements which would take advantage of the extremely large telescopes that will come online over the next decade. Section 4.7 summarizes the opportunities to make use of Rubin Observatory to study cosmology after the completion of LSST. Finally, Section 4.8 describes areas in which small investments in research and development projects could potentially enable new instrumentation or methods for cosmological measurements in the future.

4.3 Context: The Experimental Landscape Today and in the Coming Decade

In the 2010s, the survey cosmology split into two natural complementary and orthogonal experimental tracks. Both started with the first iteration of the Sloan Digitial Sky Suryve, which was both an imaging and a secptroscopic experiment. After that, the more specialized instruments followed. On the photometric, imaging track we saw early experiments such as Pan-Starrs and later Kilo-Degree Survey (KiDS) and more recently Dark Energy Survey (DES). The experiments focus on taking images of the data and measuring fluxes and shapes of extragalactic objects over large parts of the sky in a few relatively wide wavelength bands. The next instrument in this track is the LSST cameara on the Simonyi Telescope at the Vera Rubin Observatory. The spectroscopic track was followed by BOSS and eBOSS, both on the SDSS telescope and has continued with DESI on the Mayal telescope. Spectroscopic track takes spectra of many object at the same time and allows a proper 3D mapping of the universe, but it requires a targetting survey and also foregoes probes that rely on shape information such as weak gravitational lensing. This track will be followed by the DESI-II and as we hope and argue for, a larger multi-purpose Stage V spectroscopic facility.

4.3.1 Dark Energy Survey

The Stage-III dark energy experiments are completed or nearing completion: the Dark Energy Survey (DES), the Hyper Suprime-Cam Subaru Strategic Program (HSC), the Kilo-Degree Survey (KiDS), and the Extended Baryon Oscillation Spectroscopic Survey (eBOSS). These surveys have demonstrated the feasibility of ambitious large-scale structure analyses, and featured extensive tests of theory, development of state-of-the-art systematics calibration, and new rigor in protecting analyses against observer bias before the results are revealed. These surveys have, thus far, provided constraints consistent with the ΛCDM model, and contributed to tightening the constraints on several of the key cosmological parameters related to dark matter and dark energy.

The DES performed a 5.5 year survey and the full data set results are not yet released. The Y3 data cosmology results have been published [10] and the results exploring extensions are to be published soon [11]. ΛCDM remains the benchmark model. The 3x2pt analysis consists of three two-point correlation functions: 1) the angular correlation function of lens galaxies, 2) the cross correlation of tangential shear of sources with lens galaxies, and 3) the correlation functions of different components of ellipticities of the source galaxies. The DES has been improving the analysis steadily- the Y3 analysis improved the PSF modeling, better shear and redshift inference including image simulation derived corrections for shear and redshift bias dies to blending and detection, and a redshift inference process that combines spectroscopic and deep multi-band photometric redshifts from deeper DES multicolor data, cross-clustering between source and higher quality photo-z and spectroscopic samples, and small scale galaxy-galaxy lensing shear ratio information. The statistical power of the Y3 data posed unique challenges for precision cosmological inference. The analysis chose to use a magnitude limited sample of lens galaxies instead of a red-galaxy selected sample, as the latter exhibited a decorrelation of lensing and clustering amplitudes.

The Y3 cosmology results are summarized in [10]. The cosmological quanity that is best constrained by the 3x2pt analysis is the overall amplitude of clustering in the low-z universe- S_8. This allows a powerful test forr consistency between growth of structure and the expansion history in the broad class of cosmic acceleration models based on General Relativity and dark energy. This test requires a CMB anchor for matter clustering amplitude at high-z and the test becomes sharper and more general when supernova and BAO data are used to constrain the expansion history. The DES probes matter clustering out to $z \approx 1$ so it constrains dark energy models on its own through the history of growth of structure over this z range. The DES Y3 analysis finds that the DES 3x2pt data and the combination of 3x2pt with BAO, external SN Ia and external redshift space distortion data are consistent with ΛCDM and consistent with the CMB measurements of Planck. The DE equation of state parameter w is measured to be $w = -1.031 \pm 0.03$. From a combination of DES 3x2pt, BAO, and a BBN constraint on $\Omega_b h^2$, a low-z measurement of H_0 can be made, $H_0 = 68.0 \pm 0.4$ agreeing with the high-z measurement. The forthcoming paper [11] explores extentions to ΛCDM using the DES Y3 cosmology results. The set of extensions is 1) dynamical dark energy w, w_a, 2) non-zero spatial curvature, 3) varying $N_{\rm eff}$, 4) light relics varying both $N_{\rm eff}$ and the effective mass, 5) deviations from GR parameterized by $\Sigma(k, z)$ and $\mu(k, z)$ respectively modifying lensing and Poisson equations and using RSD data, 6) variation of growth rate of structure parameterized by independent σ_8 in different redshift bins.

The DES also had a deep field, weekly cadence time domain experiment aimed at cosmology with Type 1a supernova. The 3 year data with spectroscopic redshifts of the hosts or SN was published in [12] and the current effort is on the full 6 year sample using photometric typing and redshifts. It is notable how valuable the deep data has been for the static 3x2pt cosmology, in addition to the pure expansion history measurement of the SN.

The DES is representative of the Stage-III projects that have established ΛCDM has a highly effective model for describing the expansion history and the growth of structure.

4.3.2 BOSS, eBOSS and DESI

Just as the Dark Energy Survey has been a leading Stage III imaging program, BOSS (the Baryon Oscillation Sky Survey) and eBOSS (the extended Baryon Oscillation Sky Survey) have been the primary Stage III spectroscopic experiments. Both efforts have utilized an upgraded instrument, the BOSS spectrograph, on the pre-existing Sloan Digital Sky Survey telescope [13]. BOSS obtained spectra of more than 1.3 million galaxies and almost 300,000 QSOs over a sky area of more than 9000 square degrees [14, 15]. It utilized selection methods updated from those used by the original Sloan Digital Sky Survey with a goal of measuring Baryon Acoustic Oscillation scale at $z < 0.7$ using Luminous Red Galaxies (LRGs) and at $z > 2.1$ using the Lyman alpha forest (i.e., hydrogen gas along the line of sight to quasars). BOSS data has also been used for a variety of other tests of cosmology, including constraints on the growth of structure from redshift-space distortions.

The eBOSS survey used the SDSS and BOSS telescopes, but applied target selection methods that were prototypes for the Stage IV DESI experiment [16]. In total eBOSS observed roughly 300,000 LRGs, 270,000 Emission Line Galaxies (ELGs), and more than 400,000 quasars (QSOs).

The eBOSS survey completed its observations in 2019, and its final cosmology results, based on a wide variety of methods including BAO distance and redshift-space-distortion measurements, were presented in papers submitted in mid-2020. The relatively short lag between these two events reflects the simpler systematics and relative simplicity and maturity of spectroscopic large-scale structure measurements; a variety of techniques have been developed and tested in the BOSS and eBOSS surveys that are now ready to be applied to future datasets.

The final eBOSS cosmology results were presented in [4]. The results are consistent with a simple ΛCDM model. If that model is extended by allowing the curvature parameter Ω_k to be free, the combination of CMB and eBOSS BAO measurements constrain it to be $\Omega_k = -0.001 \pm 0.0018$. Similarly, if the equation of state parameter of dark energy $\frac{w=P}{\rho}$ is free, the resulting constraint is $-1.034^{+0.061}_{-0.053}$, consistent with the ΛCDM value of -1. Measurements from BOSS and eBOSS provide play a dominant role in combined Stage III constraints (including Planck, DES, and Pantheon supernova measurements) on the cosmic matter density parameter Ω_m, the dark energy density parameter Ω_Λ, the curvature parameter Ω_k, the power spectrum normalization σ_8, and the Hubble parameter H_0, with smaller but nonnegligible contributions to constraints on the equation of state parameter w and the sum of neutrino masses Σm_ν [4].

Although science analyses of Stage III imaging surveys are still ongoing, the first DETF Stage IV spectroscopic dark energy experiment, the Dark Energy Spectroscopic Instrument (DESI) survey, is now well underway. DESI utilizes a new instrument (of the same name) installed on the 4m diameter Mayall telescope at Kitt Peak National Observatory, which is operated by the National Optical-Infrared Astronomy Research Laboratory (NOIRLab). This instrument incorporates a camera with 3 degree diameter field of view, coupled to five thousand robotic fiber positioners that carry light to a set of 10 identical spectrographs covering the wavelength range from 360-980nm. In the course of its five-year survey, which began in May 2021, DESI should measure redshifts of more than 40 million objects over a sky area of at least 14,000 square degrees, including more than 9 million bright galaxies at redshifts $z < 0.4$, more than 7 million LRGs at redshifts $0.4 < z < 1.1$, 16 million ELGs at redshifts $0.6 < z < 1.6$, and more than 2 million QSOs, most at $z > 1$. After roughly one year of survey operations, DESI has already attained over 30% of the planned sample size; it is likely that more objects than originally planned will be observed by the end of the survey in 2026.

4.3.3 The Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST)

The LSST survey will begin scientific operations sometime in the summer or fall 2024. VRO observatory has been conceived as the Dark Matter telescope in 1996, where the community has first recognized the opportunity allowed by the large etendue telescope with a compact optical design focusing enabling rapid surveying of the sky that is the same time deep (due to large mirror area and field of view), wide (covering large fraction of the total available sky) and fast (relying on short exposures and periodically returning to the same parts of the sky to enable time-domain science). This visionary project will finally start taking data, almost three decades after conception.

LSST will take 10 years to complete and will offer a foundational dataset for cosmological science that requires imaging. There are four main cosmological probes for LSST: weak and strong lensing, supernovae Ia and clusters of galaxies. LSST will be transformative in each of them, significantly improving on the current state of art from the Dark Energy Survey. In many respects, experience with the DES is an incredible training ground for data analysis with the LSST. Moreover, owing to its large sky coverage and depth, LSST will enable numerous cross-correlation opportunities with the spectroscopic surveys as well as CMB.

Finally, LSST will play an essential role in providing targeting information for spectroscopic experiments by providing the most deep and uniform catalog from which to pick sources for observation. We expect that billions of sources will be available for spectroscopic follow-up spanning the entire LSST redshift range, with applications to both static and time-domain science.

4.3.4 Wider Context: CMB-S4 and space-based surveys

In the wider cosmological data context, there next decade will see data from several other important experiments. Among the experiments with significant DOE involvement, the CMB-S4 will be the groundbreaking cosmic microwave background experiment. It will measure the fluctuations in the Cosmic Microwave Background in polarization both at the coarse angular scales with the purpose of measuring the gravitational waves from the early universe and at the fine angular scales with the purpose of measuring the radiation content of the Universe. Most importantly for the CF4 physics, it will provide numerous cross-correlation opportunities with the low redshift probes. Among them, the most important are the the weak lensing mass maps inferred from distortions of the CMB maps and the Sunyaev-Zeldovich maps that will enable better understanding of hot ionized gas in the universe.

There are also several NASA and European Space Agency (ESA) space-missions with cosmologically relevant science goals. ESA's Euclid will launch in 2023 will take images and spectra of sky and will be the first space-based instrument focused on a cosmology survey in optical. It has great synergies with LSST: its premium resolution will enable important solutions for deblending and weak lensing calibration while LSST will have better flux measurements enabling better photometric redshifts. NASA's Nancy Grace Roman Space Telescope (NGRST) is planned to launch in 2026 and is instrumentally a stronger mission: it has a larger mirror and more detectors with better spatial resolution in the infrared. It will focus on smaller areas of sky, bringing complementary information at depths more comparable to what LSST will reach.

Finally, SPHEREx is a different kind of mission. It has a considerably smaller mirror and lower spatial resolution than Euclid or NGRST, but it will take data using a linearly variable filter, thus essentially measuring low-resolution spectra in coarse pixels across the entire sky. This will enable study of structure in the Universe at the largest scales; it has potential to measure non-Gaussianities at higher precision than Euclid or NGRST. It too will provide numerous cross-correlation opportunties with low-redshift experiments, including LSST and DESI.

4.4 Opportunity: Massively Multiplexed Spectroscopy

It is possible that the underlying cause of cosmic acceleration will remain unknown when the Stage IV surveys are completed. If the cosmic equation of state parameter w is near but not equal to -1, or alternatively if departures from GR on cosmic scales are weak, they may not be detected with the constraining power of upcoming surveys, leading to the need for more powerful experiments if we are to make advances.

However, with multiple experiments underway with very different strategies and systematics, it is distinctly possible that they will obtain discrepant results. In that case, it will be necessary to build on Stage IV analyses by obtaining better measurements using the methods with fewest systematics (but perhaps less potential constraining power), much as lepton colliders have been used to obtain easier-to-interpret results at lower energies than those which hadron colliders could attain.

In either of these scenarios, we would wish to have access to massively multiplexed (i.e., capable of observing large numbers of objects at once) spectroscopic instruments on large-aperture telescopes. Such a capability would enable improved constraints on cosmic acceleration from measurements of the baryonic acoustic oscillation distance scale, the amplitude and shape of the power spectrum as traced by multiple populations of galaxies and gas clouds, and the growth of structure as measured by redshift-space distortions. The same datasets that would enable these studies would also provide constraints on the sum of the masses of all neutrino species, the nature of cosmic inflation, and on models that feature an early phase of accelerating expansion due to a now-negligible component of the universe ("early dark energy" models).

A Stage V spectroscopic facility, which would provide massively-multiplexed spectroscopy on a large (preferably > 10m diameter) telescope is in many ways the obvious follow-up to the deep imaging surveys from Rubin Observatory, Euclid, and the Roman Space Telescope that will be obtained during the Stage IV era. Those surveys will provide only limited redshift information. Spectroscopy of faint objects – which requires a large telescope (or else inordinately extreme exposure times, which would then stringently limit the area covered) – can provide detailed information on the distribution of objects in the line-of-sight direction, adding value beyond the rough ("photometric") redshift estimates attained from imaging surveys. This enables higher signal-to-noise and lower-systematics measurements of large-scale structure, but also can provide statistical redshift information to imaging-only projects via cross-correlation measurements as a function of spectroscopic z.

Conversely, targeting large samples of faint objects for spectroscopy requires deep imaging to select desirable targets. Such data is now available over only limited areas, but the Stage IV surveys will provide suitable catalogs for selecting spectroscopic targets over $> 20,000$ square degrees of sky. Lessons learned from DESI and further advances in miniaturization and mass production should enable enhanced instrument capabilities compared to what could be made today. As a result, it is reasonable to target bringing new spectroscopic capabilities online before the end of the Stage IV era.

We emphasize that **a Stage V spectroscopic facility would greatly advance a wide variety of science areas**, particularly enhancing cosmic studies of dark matter as described in the report of the Snowmass CF3 Topical Group (Chapter 3 of this document). They have been called out as a key need in a wide variety of community reports both across subfields and around the world [17, 18, 19, 20, 21, 22], offering the potential that the US high energy physics community could collaborate with other interested groups and nations to share costs, while still developing new capabilities that would allow greatly enhanced studies of cosmology.

Even if the problem of cosmic acceleration is solved in the coming decade, massively multiplexed spectroscopic telescopes **would remain a high priority**, as they provide extremely flexible capabilities that will be valuable for addressing whatever the most pressing questions of the day may be. The first large ($\sim 10^6$ targets) spectroscopic survey from the Sloan Digital Sky Survey (SDSS) provides an excellent demonstration of this. A key goal for this survey was to measure the overall shape of the galaxy power spectrum in order to constrain the product of the cosmic matter density Ω_m and the Hubble parameter H_0, in the hope of resolving the key cosmology question in the mid-1990s of whether $\Omega_m \sim 0.3$ or 1. Instead, by the time SDSS began collecting data in earnest, evidence for cosmic acceleration had provided an alternative answer to the conundrums of 1990s cosmology, so the original goal for SDSS became a much lower priority. However, instead SDSS had an extremely high impact of cosmology by detecting the Baryon Acoustic Oscillation signal in galaxy clustering and demonstrating its use to constrain the expansion history of the Universe. Similarly, we can anticipate that even if the reasons we would most highly wish to have a massively multiplexed spectroscopic capability a decade from now may be different from what we currently think those reasons would be, those needs will surely exist.

In the remainder of this section, we will first examine the potential of new, larger spectroscopic surveys to constrain the nature of cosmic acceleration directly (subsection 4.4.1); summarize other ways in which such surveys can constrain cosmology (subsection 4.4.2); investigate the potential to improve constraints from Stage IV imaging surveys by using a Stage V spectroscopic facility (subsection 4.4.3); and finally, will summarize the characteristics and status of planned and proposed options for implementing such a survey (item 4.4.5). These projects are at an early enough stage that we focus on the general need for a Stage V spectroscopic facility rather than on a specific implementation.

4.4.1 Stage V Spectroscopic Surveys to Investigate Cosmic Acceleration

Based on both experience with prior and current-generation spectroscopic surveys such as eBOSS and DESI and theoretical predictions, it is clear that there are two distinct regimes where it should be possible to make major advances over current experiments. One option is to obtain denser sampling of the Universe at modest redshifts ($z < 1.5$) in order to exploit the extensive information on the growth of structure over time that is potentially available at modestly nonlinear scales, with a focus on the era when dark energy contributions to the mass-energy density became dominant. The second possibility is to study cosmology using samples of galaxies, rather than only quasars/quasistellar objects (QSOs) as in eBOSS and DESI, at higher redshifts ($z > 1.5$). Such samples would not only enable better baryon acoustic oscillation (BAO) measurements of the distance scale to high z, but also be optimal for studying the clustering at the very largest scales, which can be sensitive to the details of cosmic inflation in the early Universe. Proposed future spectroscopic facilities could be capable of observing large samples of both low- and high-redshift galaxies as well as stars in the Milky Way halo (for constraining the nature of dark matter), **simultaneously**.

Opportunities at lower redshifts: A Snowmass white paper submitted to this topical group [6] explores the case for increasing the density of samples at lower redshifts ($z < 1.5$) in detail. Measuring clustering statistics with a larger sample improves the signal-to-noise of measurements the most at smaller scales (corresponding to larger wave number k for the power spectrum $P(k)$). Errors in clustering measurements improve only slowly with sample size once the product of a sample's mean number density $\overline{n}$ and power spectrum, $\overline{n}P(k)$, is substantially larger than one [23]. At scales which are only modestly non-linear today and where the power spectrum is greater, $k \sim 0.2h^{-1}$ Mpc (comoving), the DESI survey now underway will have sufficient density to attain this goal to redshift $z \sim 1$. However, at smaller scales where the clustering of dark matter should evolve non-linearly, $k \sim 1h^{-1}$ Mpc (comoving), densities will be sufficient only at $z < 0.4$. This leaves substantial room for improvement by enlarging samples at modest redshifts.

Such enlarged samples will aid studies of cosmic acceleration by improving constraints on the growth of structure and redshift-space distortions. Smaller, nonlinear scales are particularly important for improving our understanding of the relationship between the observed clustering of galaxies and the underlying distribution of dark matter; uncertainties in this mapping can lead to systematic errors in the determination of the rate at which the amplitude of large-scale-structure has grown over time, a key probe of cosmic acceleration. Similarly, our level of understanding of the relationship between the *velocity distribution* of galaxies and the underlying distribution of velocities of dark matter particles within halos limits the range of scales that can be included in studies of cosmic acceleration based upon redshift-space distortions, including critical tests of General Relativity. These astrophysical systematics are again best studied at small scales where having denser samples will substantially improve signal-to-noise ratios.

Additional gains will come from the broader range of galaxies that would by necessity be included in enlarged moderate-redshift samples. Galaxies with different formation histories trace dark matter differently. For instance, galaxies with low star formation rates and red restframe colors have stronger clustering than the underlying dark matter distribution, while the bluest, most highly star-forming galaxies avoid the greatest concentrations of matter and are less clustered [24]. These differences are frequently summarized by the large-scale-structure bias b, defined such that the observed two-point correlation function of galaxies, ξ_g, is equal to $b^2\xi_m$, where ξ_m is the underlying clustering of dark matter. The mapping from the clustering of galaxies to the power spectrum of dark matter depends on b (including any dependence it has on scale); so, too, does the amount of redshift-space distortion observed from a given growth rate [25]. As a result, being able to make the same sets of measurements using galaxy samples having very different levels of large-scale-structure bias provides vital critical consistency checks on the impact of astrophysical systematics. Additionally, by combining clustering measurements made using differently-biased samples that are tracing the same underlying structure of dark matter, it is possible to reduce or remove the contributions of sample/cosmic variance to errors in clustering measurements, further improving constraints [26].

Obtaining high-density spectroscopic samples at low redshift will yield further benefits when combined with other datasets. For instance, such dense maps can help with determining the sources of gravitational wave detections. Kilonovae are likely to preferentially occur in massive, early-type galaxies [27]; those are precisely the sorts of galaxies that will dominate denser samples at $z < 1$. Even if the specific host galaxy of a gravitational wave source cannot be identified, the dense maps of the moderate-redshift Universe that

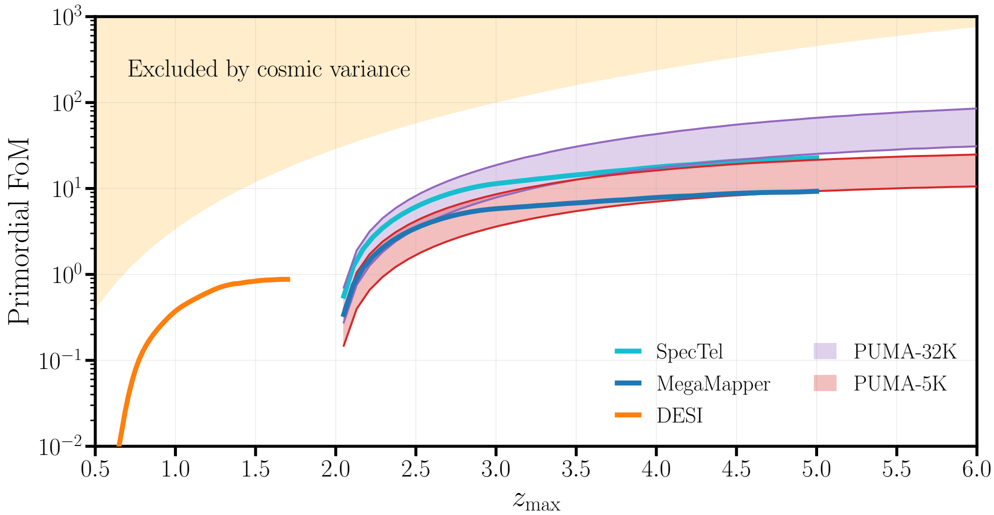

Figure 4-1 Primordial FoM $\equiv 10^{-6}\,N_{\rm modes}$ as a function of $z_{\rm max}$ for the DESI Emission Line Galaxy sample, as well as estimates based on strawman designs for PUMA (-5K and -32K), MegaMapper and SpecTel surveys. For PUMA, we consider both optimistic and pessimistic foreground models, which correspond to the boundaries of the shaded regions. The boundary of the shaded orange region is the cosmic variance limit for an all-sky survey, assuming $b(z) = 1$. Reproduced from [7].

could be obtained with new facilities would enable improved standard-siren tests on cosmology by providing measurements of the redshift distribution along the line of sight to a given event, constraining its likely redshift. Additionally, new surveys would provide spectroscopic redshift measurements for large numbers of galaxies that will at some point host supernovae that will be found by the Rubin Observatory Legacy Survey of Space and Time (LSST); this dense sampling of supernovae with known redshifts will be particularly valuable in the nearby universe, where the peculiar velocities of SNe Ia provide a valuable probe of cosmic acceleration [28].

Opportunities at higher redshifts: A second Snowmass white paper submitted to this topical group [7] has investigated the science opportunities that would be opened up by developing new, much larger samples of $z > 2$ objects with spectroscopic redshifts. In current-generation surveys, the BAO distance scale in this regime has been traced only using quasars and Lyman alpha-absorbing gas along our lines of sight to them. Since quasars are rare, sample sizes have been limited by necessity, with number densities falling well short of $\overline{n}P(k)$= 1 at relevant scales. As a result, distance errors can be reduced if redshifts can be measured for greater numbers of high-redshift objects that current samples are providing.

The MegaMapper and Maunakea Spectroscopic Explorer projects have proposed to target Lyman-break galaxies [30] and/or Lyman-alpha emitting galaxies [31] at $z > 2$, which are much more common than quasars. The larger collecting area of these telescopes compared to current-generation projects such as DESI enables redshift measurements for fainter objects in a given exposure time, making redshift measurements for large samples of high-redshift galaxies more feasible. As a result, these experiments are predicted to be capable of producing measurements of the BAO distance scale to redshifts $2-5$ with $\sim 0.5\%$ errors in four separate redshift bins (see Figure 4-2), in contrast to the $\sim 2.5\%$ errors expected from a combined analysis of DESI quasars and Lyman-alpha emitters [32].

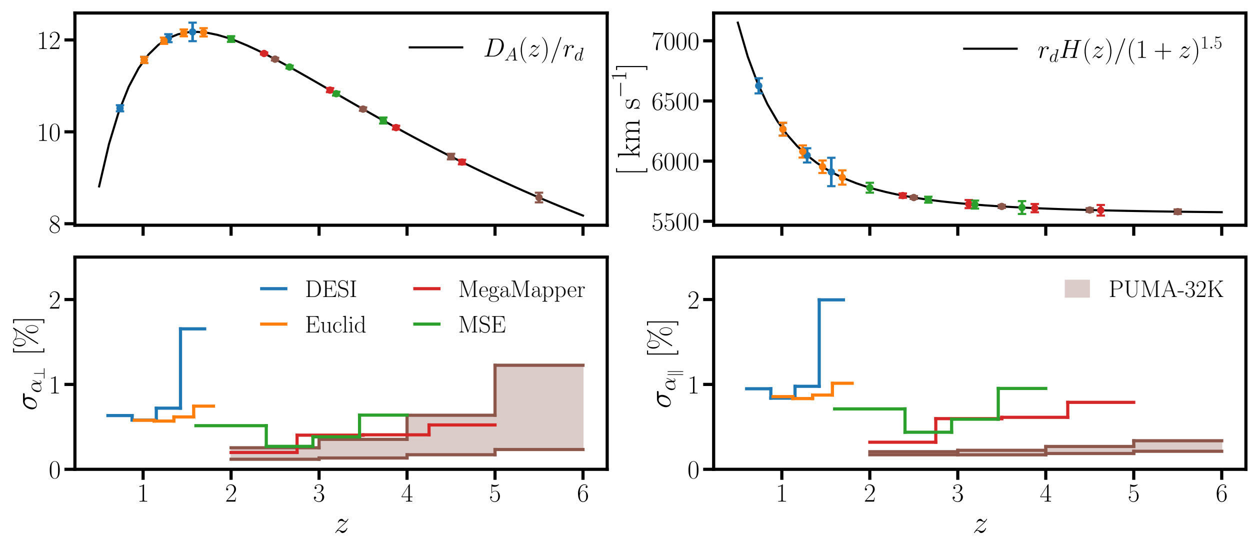

Figure 4-2 Error on the parameters $\alpha_\perp, \alpha_\parallel$ from the reconstructed power spectrum, which can be interpreted as relative errors on $D_A(z)/r_d$ and $r_d H(z)$ respectively. The line for DESI includes constraints from the ELG sample only. The boundaries of the shaded regions denote optimistic/pessimistic foreground assumptions for the 21-cm surveys. In the top panels we show the error bars for the optimistic case. Reproduced from [7].

Furthermore, by combining BAO and redshift-distortion measurements from these high-z samples, the total energy density of dark energy (not just the distance to a given redshift) can be constrained with $< 2\%$ errors at redshifts up to $4--5$, constraining the space of possible models for cosmic acceleration significantly.

4.4.2 Other Impacts on Cosmology from New Spectroscopic Capabilities

Although this report focuses on the problem of determining the cause of the accelerating expansion of the Universe, it is important to note that the *same datasets* that future spectroscopic facilities would obtain for that purpose would also enable a variety of other tests of cosmology. We focus on a number of areas of particular current interest: the total mass of all neutrinos; the level of non-Gaussianity in the primordial power spectrum as a probe of inflation; the possibility of a phase of accelerating expansion at high redshifts (after inflation and well before the present day), generally referred to as "early dark energy;" and current tensions in measurements of the cosmic expansion rate and the amplitude of the matter power spectrum (see Figure 4-4). However, we emphasize that the set we describe here is not exhaustive; indeed, based upon the history of the field to date, it is likely that new, valuable methods for cosmological tests will continue to be developed after this report is completed. In addition to all of these areas, a Stage V spectroscopic facility could simultaneously perform surveys that would help to constrain the nature of dark matter, as described in the CF03 Topical Group report (Chapter 3 of this document).

Constraining the total mass of neutrinos: Neutrino oscillation experiments constrain the difference in the square of the mass of each member of a pair of neutrino mass eigenstates, $\Delta(m^2)$. However, this leaves the actual mass of each eigenstate ambiguous, and even leaves open the possibility that the hierarchy of neutrino masses does not match the ordering of the masses of other leptons (such that, e.g., the second

	Experi-ment type	Concept	Redshift Range	Primordial FoM	Time-scale	Technical Maturity	Comments
DESI	spectro	5000 robotic fiber fed spectrograph on 4m Mayall telescope	$0.1 < z < 2.0$	0.88	now	operating	
Rubin LSST	photo	*ugrizy* wide FoV imaging on a 6.5m effective diameter dedicated telescope	$0 < z < 3$	-	2025-2035	on schedule	Targeting survey for next generation spectroscopic instruments
SPHEREx	narrow-band	Variable Linear Filter imaging on 0.25m aperture from space	$0 < z < 4$	-	2024	on schedule	Focus on primordial non-Gaussianity
MSE+†	spectro	up to 16,000 robotic fiber fed spectrograph on 11.25 m telescope	$1.6 < z < 4$ (ELG+LBG samples)	< 6.1	2029-	high	
MegaMapper	spectro	20,000 robotic fiber fed spectrograph on 6m Magellan clone	$2 < z < 5$	9.4	2029-	high	Builds upon existing hardware and know-how
SpecTel†	spectro	20,000-60,000 robotic fiber fed spectrograph on a dedicated 10m+ class telescope	$1 < z < 6$	< 23	2035-	medium	Potentially very versatile next generation survey instruments
PUMA	21 cm	5000-32000 dish array focused on intensity 21 cm intensity mapping	$0.3 < z < 6$	85 / 26 (32K / 5K optimistic)	2035-	to be demonstrated	Very high effective number density, but $k_\parallel$ modes lost to foregrounds
mm-wave LIM concept	mi-crowave LIM	500-30000 on-chip spectrometers on existing 5-10m telescopes, 80-300 GHz with R$\sim$300-1000	$0 < z < 10$	up to 170	2035 -	to be demonstrated	CMB heritage, can deploy on existing telescopes, signal uncertain, $k_\parallel$ modes lost to foregrounds & resolution

Table 4-1 Table comparing current and next generation experiments capable of performing 3D mapping of the Universe. The upper part of the table shows existing and funded experiments, while the lower part is focused on proposed future facilities. See [29] for further details. † We have computed the FoM for MSE and SpecTel assuming they performed a full time LBG/LAE survey – such a survey was not part of their proposals and those collaborations have not committed to doing any such survey. For their proposed surveys the FoM is significantly lower. Adapted from [7]

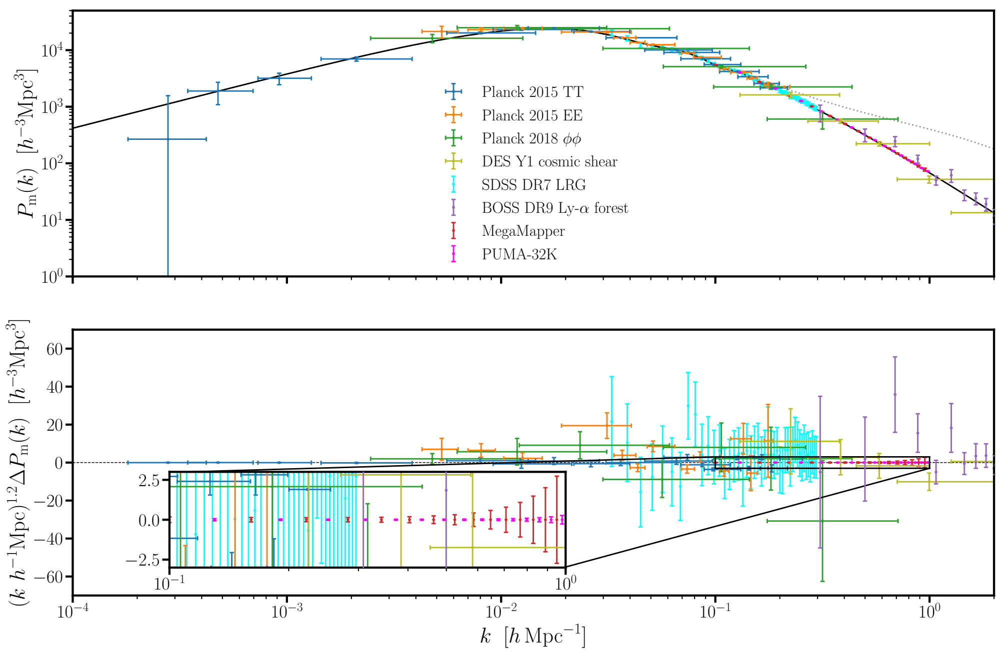

Figure 4-3 Measurements of the linear matter power spectrum at $z = 0$. For both MegaMapper and PUMA-32K we show projected constraints for 15 linearly spaced k-bins between 0.1 $h\,\mathrm{Mpc}^{-1} \lesssim k \lesssim 1\ h\,\mathrm{Mpc}^{-1}$. This figure is reproduced from [7] and adapted from refs. [**?**, **?**, 29].

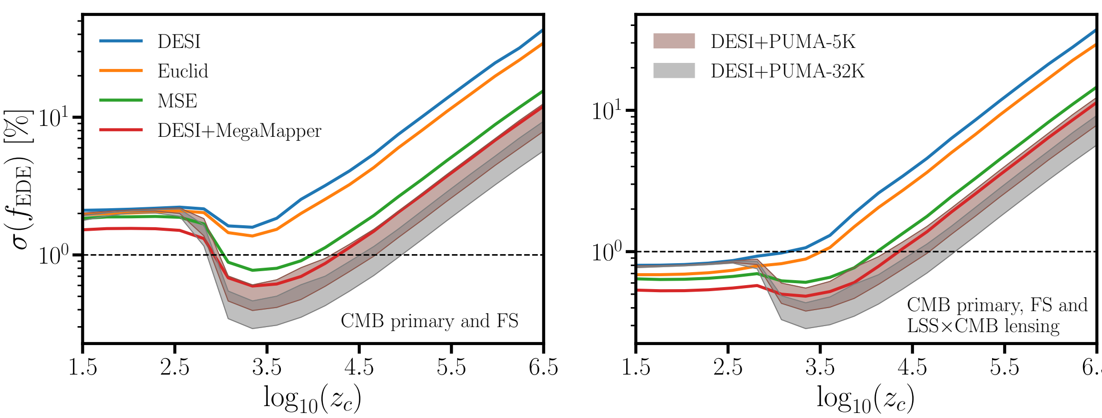

Figure 4-4 Constraints on the maximum amplitude of early dark energy (f_{EDE}) as a function of the time at which EDE peaks z_c, assuming $\theta_i = 2.83$. We include a Planck+SO prior on ΛCDM for all experiments. In the left panel we show constraints from full shape (FS) measurements only, while in the right panel we include a prior on ΛCDM and nuisance parameters from SO lensing and cross-correlations with the respective galaxy surveys. Reproduced from [7].

mass eigenstate has a mass m_2 that is greater than the mass of the third eigenstate m_3). Since the nonzero masses of neutrinos are one of the few indications we have of physics beyond the Standard Model, better constraining these masses and their hierarchy is an important problem in the field.

In contrast to neutrino oscillation experiments, cosmic spectroscopic surveys are sensitive to the *total* mass of all varieties of neutrinos (i.e., the sum $m_1 + m_2 + m_3$). This sensitivity arises because neutrinos affect the growth of cosmic density fluctuations in a scale-dependent manner. If the total mass in neutrinos is high, the power at small scales is reduced as neutrinos will not be gravitationally bound to overdensities due to their high velocities, and instead will stream away, diluting the gravitational potential. However, neutrinos also affect the growth of clustering at large scales, as in the early universe they were highly relativistic and affected the growth of perturbations in the same way as radiation, but at later times they become non-relativistic and instead have a matter-like effect. The strength of this effect again will depend on the total mass of all neutrino eigenstates. Since peculiar-velocity measurements directly measure the inflow of matter towards overdensities, they can provide direct measures of growth rates that complement inferences from the galaxy power spectrum [28].

Both high-density/low-redshift and high-volume/high-redshift samples will enable improved constraints on neutrino masses. At low redshift, we expect that being able simultaneously to measure and compare the clustering of many different populations that each trace the matter differently to lead to an improved understanding of the relationship between the clustering of galaxies and of dark matter. Such improvements could enable matter power spectrum information at small scales, where neutrino free-streaming should affect the observed signals, to be extracted. Similarly, the expected improvements to our understanding of the relationship between observed redshift-space distortions and the underlying flows of dark matter that should come from dense samples would enable neutrino mass constraints from redshift-space distortions to be interpreted with confidence. At higher redshifts, the primary improvements to neutrino mass constraints will come from having better power spectrum measurements at large scales; high-z spectroscopic samples from future surveys could cover an extremely large volume of the universe, improving power spectrum measurements at the largest scales.

Testing theories of inflation: The nature of the field which led to inflation in the early universe remains a key open question in high energy physics, with only limited means to explore it [33]. Measurements of the matter power spectrum at large scales where it has evolved only linearly provides a probe of the initial power spectrum of fluctuations left behind after inflation, providing one of the few ways we can explore this phenomenon. Strong features in the potential of the inflation field can leave an imprint that can be detected, so long as we have sensitive measurements of the large-scale power spectrum [**?**]. Large-area surveys of the universe at high redshift, as discussed in [7], are optimal for this work as they will measure clustering within an unprecedentedly large volume of the Universe. This will provide measurements of a much larger number of power spectrum modes than current surveys cover, as illustrated in Figure 4-1. The limited volume of the Universe which low-redshift surveys can cover make them much less well-suited to this work.

Additionally, some models of the inflation potential lead to non-Gaussian fluctuations in density after inflation. These non-Gaussianities can manifest as a scale dependence in the apparent bias between the clustering of galaxies and of matter at the very largest scales. Again, detecting these signals is best done at high redshift where the number of modes with large spatial scales will be greatest due to the larger volume available per unit z. Proposed new spectroscopic survey facilities have the potential to measure the primordial non-Gaussianity parameter f_{NL} with uncertainties of ± 1, which is sufficient to distinguish single-field from multi-field inflation models [**?**]. Due to the three-dimensional information provided by spectroscopy and their low cosmic variance, proposed high-z spectroscopic surveys should yield stronger constraints on f_{NL} than can be achieved from CMB measurements.

Testing for earlier phases of cosmic acceleration: In the simplest models, dark energy behaves as a cosmological constant with fixed energy density at all redshifts. In such scenarios its contribution to the mass-energy density of the universe remains subdominant until late times (after the density of matter and radiation has decreased due to the Universe's expansion); dark energy represents almost 70% of the mass-energy density today, but would be $\sim 7.5\%$ at $z = 2$ and $\sim 1\%$ at $z = 5$.

However, the behavior is different for other models of dark energy; whereas a cosmological constant has an equation of state parameter (corresponding to the ratio of pressure to energy density $w = P/\rho$) of -1, a variety of "tracker" models of dark energy only asymptotically approach that value at late times, and will have significantly different values of w at $z > 2$ [34]. As a result, measurements of the impact of dark energy at $z = 2 - 5$ have the potential to rule out a variety of models. High-redshift surveys with a future Stage V spectroscopic facility can determine the energy density of dark energy with uncertainties of < 2% of the critical density of the universe across this redshift range via the combination of BAO and redshift-space distortion measurements.

Additionally, it is possible that there was an earlier phase of accelerated expansion at much higher redshift that was overwhelmed by the matter density at later times. Such "early dark energy" models have been invoked to resolve the apparent discrepancy between the lower value of the Hubble parameter inferred from CMB and BAO measurements and the higher value measured from the local distance ladder (cf. [35] and references therein). However, if there were a phase of early accelerating expansion, the growth of matter perturbations would be affected. As a result, measurements of the matter power spectrum at late times can constrain the history of the Universe at $z > 3000$.

Both low-redshift and high-redshift surveys with new spectroscopic facilities can help to constrain early dark energy models. At low redshift, the availability of dense sampling with multiple tracers having different large-scale-structure biases should allow a better understanding of the mapping between galaxy clustering and the underlying matter power spectrum, as well as providing multiple cross-checks. At higher z, the availability of a larger volume with more power spectrum modes sampled provides its own advantages. Future survey facilities can enable the fraction of the total energy density in an early dark energy component to be determined to better than 1% at redshifts spanning from 500 to 10^4 [7].

Tensions in measurements of the Hubble Constant: Spectroscopic surveys have played a key role in investigating tensions between measurements of the Hubble parameter H_0, which provides a measure of the present-day cosmic expansion rate, based on low-redshift versus high-redshift measurements [35]. In particular, BAO measurements effectively determine distances using a scale calibrated using the cosmic microwave background acoustic peak at high redshift, providing an 'inverse distance ladder' calibrated in the early Universe. Supernova distances can be calibrated to match the BAO scale at $z \sim 0.5$, allowing a CMB-based distance scale to be measured at redshifts as low as $z = 0.02$ (as in [36]). Equivalently, BAO-based determinations of H_0 can be compared to measurements made using standard candles calibrated with a low-redshift distance ladder. The eBOSS survey found that the resulting inverse-distance-ladder value of H_0 is consistent with the value inferred from Planck CMB measurements and inconsistent with local mesurements [4]; the inverse-distance-ladder approach gives a value $H_0 = 67.87 \pm 0.86$. If one is willing to assume a baseline ΛCDM cosmology with no extensions, eBOSS obtains a value $H_0 = 67.35 \pm 0.97$ even without the incorporation of information from the CMB from the combination of BAO and Big Bang nucleosynthesis measurements. Future surveys with better BAO measurements at higher redshifts should provide stronger constraints still from this CMB-independent approach. In combination with the constraints on early dark energy models that they will provide, a Stage V spectroscopic facility could play an important role in exploring both the nature of and the physics underlying the tension in current Hubble parameter measurements.

Tensions in measurements of the amplitude of the matter power spectrum: Experiments have repeatedly found that determinations of the amplitude of the matter power spectrum inferred from CMB temperature and polarization maps are in tension with measurements based on galaxy clustering, lensing, redshift-space distortions, or the Sunyaev-Zel'dovich effect made at lower redshifts, as reviewed in [35]. Lower-redshift samples will include galaxies with a wide range of large-scale structure biases; however, since *all these galaxies trace the same underlying web of matter*, the inferred matter power spectrum from different tracers at the same redshift should agree. If not, we can infer the presence of systematics in current methods, and should give any apparent tension lower credence.

A spectroscopic facility would enable power spectrum measurements using many different techniques, not just using multiple tracers. From spectroscopic data alone, one can infer the underlying power spectrum with the observed clustering and a simple bias model, but furthermore higher-order correlation function measurements (e.g., determination of the galaxy bispectrum) can enable the large-scale-structure bias to be inferred directly, improving matter power spectrum measurements. Redshift-space distortions within the spectroscopic samples provide another constraint on the clustering of matter.

One can go even further by combining spectroscopic samples with measurements based on other datasets. At lower redshifts, galaxy-galaxy lensing, which would combine spectroscopic samples in the foreground and Rubin Observatory (or space-based) lensing distortiion measurements for background objects, will provide an another method of mapping the overall distribution of matter. At higher redshifts ($z > 1$) the amplitude of CMB lensing around foreground spectroscopic objects will provide another means of mapping the distribution of matter. Cross-correlations with Sunyaev-Zel'dovich or X-ray maps can provide additional information. By enabling high-precision measurements using a wide range of methods with disparate systematics, with redshift coverage spanning from $z \sim 0.1$ to $z \sim 5$, **surveys with a Stage V spectroscopic facility should play a key role in assessing the nature and redshift-dependence of tensions in measurements of the amplitude of the power spectrum.**

4.4.3 Enhancing Stage IV imaging surveys via spectroscopy

A Stage V spectroscopic facility can also enable improved constraints on cosmology by unlocking the full constraining power of near-future experiments such as the Vera C. Rubin Observatory and CMB-S4. These new capabilities will provide information-rich datasets, but will provide only limited information about redshift (in the case of Rubin Observatory) or none at all (CMB-S4). Both new analyses of the large, wide-area surveys discussed above and smaller-area, more focused spectroscopic programs with new facilities can help to fill in the missing information and yield stronger constraints on cosmic acceleration from imaging-only projects at a fraction of their total cost.

Improving photometric redshifts from the Vera C. Rubin Observatory: Over the course of the ten-year Legacy Survey of Space and Time (LSST), the Rubin Observatory will provide images of more than 20,000 square degrees of sky through six filters, providing coarse spectral information for the billions of objects detected spanning from near-ultraviolet to near-infrared wavelengths. This coarse spectral information can be used to estimate the redshifts of individual objects or the overall redshift distribution of ensembles of galaxies; these imaging-based estimates are known as *photometric redshifts* or *photo-z's*.

Photometric redshift estimates have the advantage of being available for all objects that are detectable by an imaging survey, at the cost of lower redshift precision for individual objects. Typical photometric redshift uncertainties σ_z are $\sim 0.02 - 0.1(1+z)$ in modern surveys, depending on the population studied and the dataset used [37], in comparison to uncertainties $<< 0.001(1+z)$ from spectroscopic data. Furthermore, for a nonnegligible fraction of objects photometric redshifts fail catastrophically to get the redshift correct; the fraction of objects with redshift errors $\Delta z > 0.15(1+z)$ (commonly labelled $f_{\rm outlier}$) reaches 5% or more in deep surveys.

Photometric redshift-dependent probes of cosmology – which include weak-lensing shear measurements, image-based large-scale-structure measurements, studies of galaxy cluster abundances, and selection of strong lens systems and supernovae for follow-up measurements [38], spanning all major probes planned for LSST

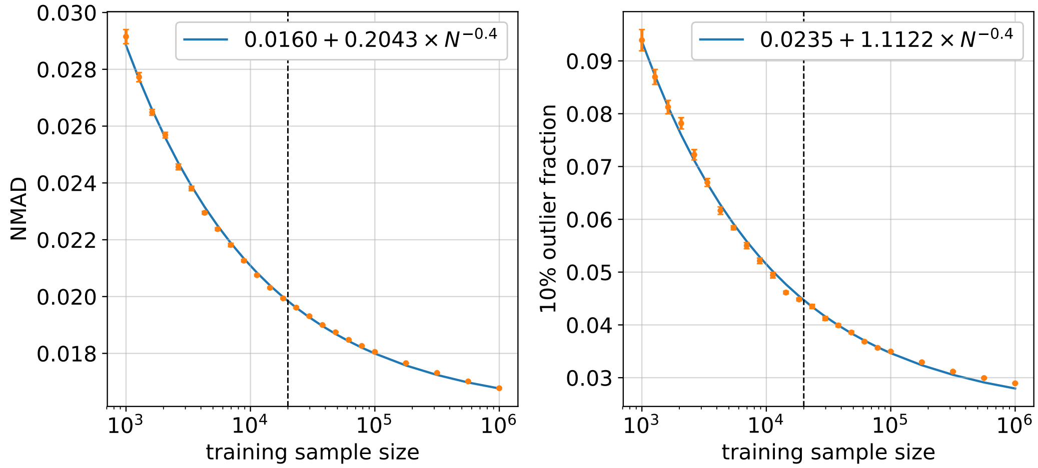

Figure 4-5 Orange points show photometric redshift errors and outlier rates versus the number of galaxies in the training set for galaxies with simulated LSST photometric errors. Photo-z's were calculated using a random forest regression algorithm. The left panel shows the photo-z error, quantified by the normalized median absolute deviation (NMAD) in $(z_{\rm phot} - z_{\rm spec})/(1 + z_{\rm spec})$, as a function of training set size; similarly, the right panel shows the fraction of 10% outliers, i.e. objects with $|z_{\rm phot} - z_{\rm spec}|/(1+z_{\rm spec}) > 0.1$. A vertical dashed line shows the sample size for the baseline training survey from [**?**]. The blue curves represent simple fits to the measurements as a function of the training set size, N. This analysis uses a set of simulated galaxies from Ref. [41] that spans the redshift range of $0 < z < 4$, using a randomly-selected testing set of 10^5 galaxies for estimating errors and outlier rates; these catalogs are based upon simulations from Refs. [42],[43], and [44].

– critically depend on obtaining large samples of spectroscopic redshifts, as described extensively in prior work [37, 8, 39]. One application is to improve the *performance* of photo-z algorithms; i.e., the uncertainties in the redshifts of individual objects. With spectroscopy of a sample of 20-30,000 objects extending as faint as the faintest objects used for LSST cosmology and distributed over multiple independent areas of sky, it should be possible to measure photometric redshifts with uncertainties approaching the expected LSST system-limited performance of $\sim 0.02(1 + z)$, rather than the $\sim 0.05(1 + z)$ achieved in deep datasets today [8, 40], as illustrated in Figure 4-5.

This reduction in uncertainties would improve the cosmological constraining power of LSST greatly, increasing the expected Dark Energy Task Force figure of merit from weak lensing and large scale structure measurements alone by 40% [45], with even larger gains to cluster cosmology likely. Such a dataset will require extensive observations to obtain; estimated survey times with different instruments and facilities are given in Figure 4.4.3, which was originally published in [8]. The proposed Stage V spectroscopic facilities would be extremely efficient at conducting such surveys; **they have the potential to greatly increase the power of LSST with an investment of only a few months of observing time.**

Because of their greater uncertainties, photometric redshift-based analyses are also dependent upon having accurate *characterization* of their error distribution (or, equivalently, of the redshift distributions of photometrically-selected samples). Moments of the redshift distribution, including the mean and standard deviation, must be determined with exquisite accuracy (with uncertainties $\sim 0.001(1 + z)$ by the end of the survey) for LSST cosmology not to suffer systematic errors that exceed random uncertainties in

Table 4-2. Time required for photometric redshift training spectroscopy

Instrument / Telescope	Collecting Area (sq. m)	Field area (sq. arcmin)	Multiplex	Total time (dark-years)
VISTA/4MOST	10.7	14,400	1,400	1.4
Mayall 4m / DESI	11.4	25,500	5,000	1.4
WHT / WEAVE	13.0	11,300	1,000	1.6
Megamapper (Magellan-like)	28.0	25,416	20,000	0.6
Subaru / PFS	53.0	4,500	2,400	0.4
VLT / MOONS	58.2	500	500	2.7
Keck / DEIMOS	76.0	54	150	6.8
Keck / FOBOS	76.0	314	1,800	0.8
ESO SpecTel	87.9	17,676	15,000	0.2
MSE	97.6	6,359	3,249	0.2
GMT/MANIFEST + GMACS	368.0	314	420	0.5
TMT / WFOS	655.0	25	100	1.2
E-ELT / Mosaic Optical	978.0	39	200	0.5[1]
E-ELT / MOSAIC NIR	978.0	46	100	0.8

[1]For E-ELT, observations in both the optical and near-IR settings are required to achieve the required wavelength coverage, increasing total time required.

cosmological parameters [38]. Because photo-z's are intrinsically uncertain, this exquisite calibration is critically dependent upon spectroscopic redshift information.

If redshifts can be robustly measured for almost all targets in the deep spectroscopic surveys that would enable optimized photo-z performance, redshift distributions and errors could be characterized to the necessary precision directly [8]. However, existing deep samples have been systematically incomplete, failing to yield secure redshift measurements for $\sim 30\%$ of galaxies in a property-dependent manner. In such a scenario, less direct methods are needed.

In that case, a promising option is to rely upon cross-correlations between photometrically-selected samples and objects of known spectroscopic redshift, as a function of the spectroscopic redshift. The two samples of objects will cluster together when they trace the same underlying large-scale-structure – i.e., when they overlap in redshift. Such cross-correlation measurements, in combination with measurements of the clustering of both spectroscopic and photometric samples on their own, can provide sufficient information to reconstruct the redshift distribution of photometric samples with fidelity. However, such cross-correlation signals are best measured from clustering at quasi-linear or larger scales using spectroscopic samples that span very large areas of sky [46]. As a result, it is desirable to have extensive, wide-area surveys that trace the large-scale structure across the full redshift range spanned by LSST cosmological samples ($z < 2 - -3$). The proposed moderate-z, high-density samples that next-generation spectroscopic facilities would enable would provide multiple tracers of structure with different biases, allowing detailed reconstruction of redshift distributions with multiple cross-checks at the redshifts where the bulk of the LSST lensing signal will originate. In turn, the proposed higher-redshift samples will improve the characterization of the higher-redshift tail of the LSST source distribution. DESI samples will only have quasars and their absorption systems as tracers at $z > 1.5$, which sample structure only dilutely and may exhibit astrophysical systematics that alter cross-correlations

[47]; by using galaxies as tracers instead, future surveys could avoid these issues. As a result, a new Stage V spectroscopic facility would have the potential to retire one of the greatest potential sources of systematic errors in LSST cosmological analyses [38].

Follow-up spectroscopy of galaxy clusters, supernovae, and strong lens systems: Because Stage V spectroscopic facilities should be able to target a large number of objects simultaneously, they can target rare objects of utility for cosmology at the same time as they conduct their primary surveys by reserving a small fraction of the fibers available. For instance, spectroscopy could be obtained for large samples of candidate strong gravitational lens systems by taking only a few fibers away from their planned survey targets, enabling optimized selection of systems for dedicated follow-up with other facilities [48].

As another example, galaxies within clusters that have been identified by Rubin Observatory or CMB experiments can be targeted simultaneously with the proposed star and galaxy surveys in order to determine cluster redshifts with precision. Furthermore, at low redshift where clusters span a large angular extent and cluster galaxies are relatively bright, redshifts for statistical samples of galaxies within individual clusters can be obtained in order to measure their velocity dispersions and calibrate mass-observable relations [8].

Similarly, measuring redshifts and spectroscopic properties for $\sim 100,000$ Type Ia supernovae discovered by Rubin Observatory would require only a small fraction of the fibers available, but would great enlarge the sizes of samples that could be used for precision supernova cosmology studies across the full LSST sky area. Such large samples can enable entirely new probes of cosmology. As an example, by comparing the measured redshifts to distances estimated from light curve fitting, one can obtain a noisy estimate of the peculiar velocities of individual supernovae. Averaging these estimates over large samples of supernovae that span a large volume, the large-scale velocity field can be measured, providing new constraints on the cosmic equation of state [49].

Unlocking additional cosmological information via cross-correlations: Measuring cross-correlation statistics (i.e., the correlation between one quantity and another as a function of separation or scale) that combine the large survey samples that new spectroscopic facilities would provide with measurements from Rubin Observatory or CMB experiments provides additional information that neither dataset can access on its own.

We have already discussed above how measuring *density* correlations between spectroscopic and photometric samples has the potential to provide detailed redshift information for Rubin Observatory studies. However, by also measuring the correlations between the density of galaxies of given properties in a spectroscopic sample and the observed weak lensing shear from photometric objects in the background to those galaxies, we can also directly study the distribution of total mass around the spectroscopic objects, and hence infer the relation between these observed samples and the underlying dark matter. In combination with the large-scale-structure bias information available in density cross-correlations, one can then study the underlying power spectrum of density fluctuations itself [50]. By providing large samples with a range of biases at $z < 1.5$ and ample sample sizes up to $z = 3+$, a future spectroscopic facility can enable multiple cross-checks of methods at lower redshift and directly infer the clustering of matter out to the highest redshifts probed by Rubin Observatory lensing.

Cross-correlations between spectroscopic samples and CMB lensing maps should be powerful as well. Whereas Rubin Observatory lensing analyses will measure shear using multiple photometrically-determined redshift bins, providing some redshift information on where the lensing mass is located, the CMB lensing signal all originates at very high redshift, with no redshift discrimination. However, by measuring the cross-correlation between spectroscopic samples and the CMB lensing signal, it should be possible to reconstruct the matter power spectrum as a function of redshift, since the contribution of each redshift to the net signal can be measured directly. For such analyses, extending spectroscopic surveys to as high redshift as is feasible would be valuable, as the efficiency of CMB lensing is greatest at $z \sim 2$ but falls off slowly. One critical advantage of cross-correlation statistics for such analyses is that spectroscopic samples will have very different systematics from CMB lensing maps; such systematics will affect autocorrelations based on a single type of sample, but vanish when cross-correlations are measured [51, **?**].

4.4.4 Proposed Stage V Spectroscopic Facilities

Several proposed dedicated facilities for Stage V-level spectroscopy were described in Snowmass Letters of Intent; we briefly summarize them here.

MegaMapper: The proposed MegaMapper facility would consist of a dedicated 6.5m diameter telescope coupled with 20,000 fiber positioners that take light to a set of DESI spectrographs covering 360-980 nm [52]. The telescope main mirror would be similar in design to those of the existing Magellan telescopes, but a hyperbolic secondary mirror and corrector lenses would enable a much larger field of view than is available at Magellan, totalling 7.1 square degrees. The telescope would be sited at Las Campanas Observatory in Chile. MegaMapper has been proposed as a collaborative project between Lawrence Berkeley National Laboratory and the Carnegie Observatories. It is estimated that construction would take 7 years from project approval, making this the earliest feasible option for a massively multiplexed facility. However, additional research and development is still needed to develop fiber positioners with the 6.5 mm center-to-center separation necessary to achieve a multiplex of 20,000 within the planned 1.2 m diameter focal plane (for comparison, DESI positioners have a 10.4 mm pitch). We note that such development could benefit any of the proposed spectroscopic facilities.

The Maunakea Spectroscopic Explorer: The Maunakea Spectroscopic Explorer (MSE) would consist of a new 11.25-14m diameter telescope with a 1.5 square degree field of view, coupled to 4000-21,000 fibers [53]. One quarter of these fibers would be coupled to high-resolution spectrographs that are poorly suited for cosmic surveys, but the remainder would use moderate-resolution spectrographs covering at minimum 360-900 nm, with a subset feeding near-infrared spectrographs covering 1-1.8 μm. Given the planned focal plane diameter of 1.3m, improvements to fiber positioner size beyond DESI would still be needed to achieve this multiplex. MSE would replace the existing Canada-France-Hawai'i Telescope at the summit of Maunakea, utilizing much of the existing infrastructure, though a new and enlarged dome would be needed to accommodate recent designs. MSE has passed a conceptual design review and the two-year preliminary design phase for it should begin in 2022; it is anticipated that science operations could begin within ten years if the schedule is technically-limited.

SpecTel: An European Southern Observatory (ESO)-sponsored study has proposed developing an 11.4m diameter spectroscopic telescope supporting a 5 square degree field of view and hosting 15,000 fibers. Some fibers may be devoted to high-resolution spectrographs or integral field unit observing modes, but most would be coupled to moderate-resolution spectrographs with a wavelength range of $360 - 1330$ nm, suitable for the surveys discussed in this report. The proposed design could achieve the nominal multiplex of 15,000 with DESI-sized fiber positioners, or higher numbers with a smaller pitch. This design delivers a worse image quality than MSE but enables a significantly larger field of view, advantageous for wide-area surveys. Such tradeoffs as well as cost and schedule needs would be evaluated in the conceptual design process, which has not yet occurred for SpecTel.

4.4.5 Considerations for Evaluating Stage V Spectroscopic Facilities

Any of the proposed Stage V spectroscopic facilities would represent a significant advance over what is possible with current resources and would enable progress on all of the science described in this section. Given this, and that all three proposed facilities are still in the process of developing designs and collaboration models, it is not appropriate to select a specific implementation yet, but rather to establish a clear process and requirements for a final selection.

In general, the ability of these facilities to contribute to cosmic frontier science will be maximized if:

1. The etendue of the system (i.e., the product of the collecting area and field-of-view, $A\Omega$) is as large as feasible while still maintaining good optical quality. Increasing etendue will increase the speed of wide-area surveys, which are critical to the proposed science.

2. The focal plane area of the system is as large as possible (again, without sacrificing optical quality) in order to increase the number of fiber positioners that can be accommodated. A minimum of 10,000 fiber positioners should be required to enable significant advances over what DESI can achieve, with 20,000 or more simultaneous positioners preferred. However, fiber-densities of more than 10,000 per square degree are likely to be excessive for wide-area science cases. However, if the instrument serves multiple science cases, the number of targettable objects naturally increases, allowing higher fiber-density designs to be efficient.

3. The spectrographs used for cosmic acceleration surveys provide continuous coverage over the full optical window from 370 to 1000 nm, with wavelength coverage extending up to 1.6 μm in the infrared desirable but not absolutely required. At wavelengths above 600nm spectral resolution should be sufficient to resolve the [OII] 3727 Angstrom doublet, providing secure redshift measurements from a single feature; this requires a resolution $R = \frac{\lambda}{\Delta\lambda} \sim 4000$ or above.

4. The collecting area of the facility should be at least as large as that of Rubin Observatory, in order to facilitate spectroscopy of faint targets (with larger collecting area preferable for faint-object science cases).

5. All else being equal, a Southern hemisphere (or at minimum tropical) site is preferred in order to maximize synergies with the Rubin Observatory LSST and with CMB experiments.

These considerations will need to be weighed against the amount of new funding needed for construction and operations in conjunction with other partners; the fraction of observing time that would be dedicated to surveys to study cosmic acceleration and dark matter; and the date when a facility would become available (e.g., LSST supernovae follow-up will not be feasible if LSST ends before construction of a facility is completed). A downselect in several years' time may be appropriate. In the meantime, research and development on the miniaturization of fiber positioner systems would help to maximize the capabilities of a new facility when it is constructed by increasing multiplexing capabilities.

4.4.6 DESI as a Bridge to the Next Generation

When it completes its five-year survey in 2026, the Mayall telescope coupled to DESI is expected to remain the most efficient capability available for wide-area spectroscopic surveys until such time as a Stage V spectroscopic facility is built. Given the much etendue and multiplex of Mayall/DESI compared to what next-generation telescopes should provide, it cannot match the surveys that they would make possible. Nevertheless, DESI should play several important roles in the intervening period. These should include:

- Performing prototype surveys that develop new target classes and observing modes for future facilities, while simultaneously producing new cosmological constraints. This would follow the successful model of the recent eBOSS survey, which applied prototype selection methods that were being explored for DESI using the leading spectroscopic survey capability available, specifically the Sloan Digital Sky Survey telescope with the BOSS spectrographs. The eBOSS survey enabled these new selection techniques to be explored and assessed, and delivered improved constraints on cosmic acceleration models. Importantly, it also helped to support the ongoing advancement of new analysis methods which are now being applied to DESI, as well as the development of a cadre of junior scientists who were well-prepared to contribute to the next generation of survey spectroscopy.

- Targeted pursuit of the most efficient science opportunities. Given its multiplexing and etendue, it is not feasible for DESI to simultaneously undertake multiple, dense surveys as has been proposed for Stage V facilities. However, it would be feasible to pursue a selected, high-value subset of that science in order to advance our understanding of cosmic acceleration sooner; some possibilities are discussed in white papers submitted to this topical group [**?**, 7]. If a Stage V facility is not going to be available in the early 2030s, there will be correspondingly more need for DESI to contribute in this way.

- Maximizing the science from near-future imaging surveys. As discussed in subsection 4.4.3, massively-multiplexed spectroscopy can enhance the science output from planned imaging surveys such as the Rubin Observatory LSST and CMB-S4. In many cases these needs are time-sensitive – particularly in the case of transient spectroscopy as for type Ia supernovae, but the quality of LSST photometric redshifts will also be limited by the availability of training spectroscopy. Because of this, the complementarity of DESI observations to planned imaging experiments and the time urgency of those observations should be given substantial weight in developing future DESI programs. In some situations, DESI may improve cosmological constraints most per unit time via spectroscopic surveys themselves, but in others DESI data may deliver a higher impact by greatly improving the constraining power of other datasets; it is likely that a combination of the two strategies will be optimal.

4.5 Opportunity: Physics with Small Projects

Follow-up observations of Type Ia supernovae: Measurements of Type Ia supernova distances have provided one of the foundational probes of dark energy and were used in its definitive discovery in the late 1990s. LSST should observe hundreds of thousands of SNe Ia at $z < 1$, an unprecedented sample that could be used to strongly constrain the expansion history of the universe.

However, to enable this science, follow-up spectroscopy from other facilities will be needed to complement LSST. This serves two main goals. The first is to provide spectroscopic classifications for "live" SNe (i.e., while they are brightest) to identify true Type Ia objects. These spectroscopic classifications will then enable the construction of optimized training samples for classifiers that use LSST photometry alone, which can then be used to assemble the next generation of SN Ia cosmology samples. Even the most advanced classification techniques cannot make robust inferences without large, homogeneous and representative training sets [54]. The second goal is to obtain spectroscopic redshifts for host galaxies of SNe that have faded away. The latter is not time-sensitive and can be performed opportunistically, perhaps even in conjunction with following up live supernovae. Since supernovae are bright for only a few months, many more supernova hosts will be available for spectroscopy at any one time than live SNe.

Table 4-3. Time required per epoch of SN host spectroscopy in LSST deep fields

Instrument / Telescope	Collecting Area (sq. m)	Field area (sq. arcmin)	Multiplex	Total time (dark-years)
4MOST	10.7	14,400	1,400	0.05
Mayall 4m / DESI	11.4	25,500	5,000	0.03
WHT / WEAVE	13.0	11,300	1,000	0.06
Megamapper (Magellan-like)	28.0	25,416	20,000	0.01
Subaru / PFS	53.0	4,500	2,400	0.04
VLT / MOONS	58.2	500	500	0.29
Keck / DEIMOS	76.0	54	150	2.04
Keck / FOBOS	76.0	314	1,800	0.35
ESO SpecTel	87.9	17,676	15,000	0.01
MSE	97.6	6,359	3,249	0.01
GMT/MANIFEST + GMACS	368.0	314	420	0.07
TMT / WFOS	655.0	25	100	0.51
E-ELT / Mosaic Optical	978.0	39	200	0.22[1]
E-ELT / MOSAIC NIR	978.0	46	100	0.19

[1]For E-ELT, observations in both the optical and near-IR settings are required to achieve the required wavelength coverage, increasing total time required.

The LSST Deep Drilling Fields will provide the best-characterized and deepest LSST SN samples. Following the very successful experience of the OzDES survey [55], the 4MOST/TiDES program will perform long-exposure spectroscopy on all bright live SNe in the LSST Deep Drilling Fields [48], but *only for the five years when 4MOST will be operational,* only half the duration of LSST. However, for fainter and more unusual supernovae, targeted follow-up with single-target spectrographs on both moderate-aperture and large telescopes will be required; this effort will require coordination.

An efficient strategy for maximizing the size of supernova samples is to measure the redshifts for their hosts. Table 4-3 (described in more detail in [8]) lists the total amount of time it would take to perform annual spectroscopy of the expected ~ 100 new $r < 24$ galaxy hosts of LSST supernovae per square degree spanning the five LSST deep drilling fields using different instruments. As can be seen, the requirements are quite modest – less than 10 nights per year with DESI would be required for this effort (though not all LSST DDFs are visible from Kitt Peak, so other facilities will be needed as well).

The sample of hundreds of thousands of SNe that will be discovered in the main Wide/Fast/Deep LSST survey has the potential to revolutionize cosmological analyses, but its constraining power will be limited if the supernova redshifts are not accurately known. Such supernovae and their hosts could be efficiently targeted for spectroscopic observations using a subset of the fibers on a survey instrument such as DESI or a Stage V spectroscopic facility at the same time that most fibers are dedicated to other surveys (such as the ones described in section 4.4), greatly increasing the science yield from LSST supernovae. 4MOST/TiDES will obtain spectra of a substantial number of supernovae in this mode during the main 4MOST survey, but that will span only part of the duration of LSST, so additional efforts will be needed. However, such an activity would require coordination between facilities and science collaborations.

Supernovae are scattered on the Hubble diagram (i.e., the inferred distance plotted as a function of redshift) primarly due to the intrinsic variation in the luminosities of SN explosions. At low redshift or when averaged over large samples, the additional scatter due to their peculiar velocities along the line of sight can be non-negligible and is useful as a cosmological probe. Peculiar velocities affect both the observed redshift and the observed flux but in a way that is not the same as transposing a supernova to a different redshift. Since peculiar velocities are correlated amongst objects that are subject to similar gravitational fields, this leads to spatially correlated residuals that allows one to extract this signal cleanly [56]. The peculiar velocity power spectrum is sensitive to the effect of gravity on the linear growth of structure. Measurements with high statistical confidence will be possible in the coming decade by exploiting the large numbers of low redshift ($z < 0.1$) SNe Ia that will be discovered in this timeframe [57]; if host redshifts can be measured for large sets of LSST supernovae across the sky, measurements will also be viable at higher redshifts [49]. With modest additional infrastructure compared to what is needed for LSST alone, this method has potential to add a competitive measurements of growth at the lowest redshifts where traditional galaxy surveys are limited by the sample variance given the small total volume available. To enable this science, the following facilities would be needed:

- *Surveys with wide-field-of-view (∼> 1 sq. deg.) imaging on a ∼2m telescope* to perform early-phase screening;
- *Targeted (IFU) spectroscopy of active SNe* to provide classification, host-galaxy redshifts and precision SN Ia absolute magnitudes; and
- *Targeted spectroscopy of host galaxies* to obtain their redshifts when they are not available from IFU spectroscopy.

The investment required would be modest, largely involving person-power for software infrastructure and operating costs, since the types of instruments required are relatively common.

Exploring cosmic acceleration with standard sirens: The standard-siren method allows geometric distances to be measured for gravitational wave (GW) sources; this is emerging as a promising way to determine the Hubble parameter independent of any distance ladders. However, future gravitational wave detectors will provide much larger samples of sources reaching greater distances, allowing the distance-redshift relation to be mapped out and enabling measurements of cosmic acceleration [**?**]. However, this would be dependent upon measuring redshifts for the sources of the gravitational waves, meaning that spectra of the electromagnetic (EM) counterparts of these sources (or their hosts) must be measured.

This presents two problems: finding the EM counterpart, and measuring its spectrum. Because the positions of gravitational wave sources are only poorly constrained (especially for near-term experiments), there will be very large numbers of EM transients consistent with the error ellipses for a given object. Finding the visible counterpart of a GW source therefore both requires searching a wide area of sky for transient sources, and selecting only a limited number of time-variable objects that are most likely to correspond to compact-object mergers. Because of its large etendue and array of broad-band filters, the Vera C. Rubin Observatory would be the most efficient option for this work, though less efficient alternatives exist as well.

One then must obtain spectra of the selected EM transients (or their host galaxies) to determine their redshifts. When there are only a few viable counterparts, there are many facilities with a range of apertures that could undertake this work by measuring spectra of one object at a time. However, when there are many potential sources distributed over a wide area of sky, the only efficient options are the widest-field-of-view multiobject spectrographs, such as DESI or a Stage V spectroscopic facility. Thus, if efficiently identifying EM counterparts for large numbers of gravitational wave sources becomes viable in the future, it would be beneficial to put in place organized target-of-opportunity programs both at Vera C. Rubin Observatory and the widest-field spectroscopic facilities to enable this effort to succeed.

Photometric redshift training spectroscopy for LSST: As was described in subsection 4.4.3, the cosmological constraining power of the Rubin Observatory LSST can be significantly increased by improving the precision of the photometric redshifts obtained via measuring spectroscopic redshifts for large sets of faint objects. Although a Stage V spectroscopic facility would be well-suited for this application, no such facilities will be available until late in the LSST survey or possibly even only after it is completed.

As a result, it would be highly valuable to undertake more limited photo-z training campaigns earlier in the progress of LSST; this would both reduce the time demands on future facilities and deliver higher-quality science from Rubin Observatory sooner. As can be seen in Figure 4.4.3, there are three modestly efficient options that would utilize 4m-class telescopes that currently exist and instruments that are operating or well underway: VISTA/4MOST, Mayall/DESI, or WHT/WEAVE. Any of these instruments would require roughly 500 dark nights to conduct the baseline LSST photometric redshift training survey, though shallower surveys would still be useful in the shorter term and require less observing time. Out of these, DESI is based in the U.S. and has been constructed and operated using DOE funding, making it the most promising 4m-class option to undertake this work.

However, by far the most efficient way to obtain the necessary training spectroscopy would be to utilize the PFS instrument on the 8m Subaru telescope in Hawai'i; it would require roughly 150 dark nights for the LSST baseline survey. Subaru time is already being dedicated to observations in support of the Nancy Grace Roman Space Telescope, which should include photometric redshift training programs with PFS; the samples needed for this overlap with, but are not identical to, those needed for LSST. A promising option would be to pursue a joint training program with NGRST using Subaru, potentially incorporating time provided to LSST as in-kind contributions as well as that provided for NGRST support. However, significant effort would still be needed to develop target samples, conduct observing campaigns, and reduce and analyze the resulting data in order to optimize the science output from LSST.

4.6 Opportunity: Physics with Extremely Large Telescopes (ELTs)

The upcoming generation of extremely large telescopes (ELTs), including the European-led Extremely Large Telescope and the US-led Thirty Meter Telescope (TMT) and Giant Magellan Telescope (GMT) will be transformative for astronomy in general. Their designs provide relatively small fields of view, which makes them poorly suited for wide-area surveys. However, their excellent sensitivity and refined adaptive optics capabilities make them uniquely capable of following up faint targets discovered by dedicated survey telescopes such as the Rubin Observatory. We outline some of the key opportunities below.

Characterizing strong lens systems: Strong lensing refers to distortions of the light from distant objects by the gravity of foreground objects that goes beyond low-order perturbations. Strongly lensed objects may be greatly distorted and exhibit multiple images; i.e., we see light from a single object appearing at several distinct points on the sky. Since light travel time along the different light paths for each image can vary by days to years, observing an intrinsically variable distant object allows us to measure the time delay between different light paths. When combined with a model for the lensing system, this allows one to determine the value of the Hubble parameter. The time delay of a strongly-lensed system is one of the very few dimensionful observables in cosmology.

Traditionally, strongly-lensed quasars have served as the time-variable sources of choice, but the first discovery of multiply lensed supernova SN Refsdal [58] has ushered in a new era for strong lensing. Measuring time delays from lensed supernovae has many advantages over using quasars, which have previously been used to measure H 0 to $\sim$ 3% assuming a ΛCDMcosmology (REF needed). Lensed supernovae require less monitoring and are less sensitive to microlensing [59], mass modeling systematics [60], and selection bias [61]. Time delays from lensed supernovae also present opportunities to observe the earliest phases of supernova explosions, to infer cosmological parameters, and to map substructure in lens galaxies impacting dark matter physics, but many more systems are needed to achieve these goals. Lens systems will require monitoring (requiring repeated imaging on smaller telescopes), but the modeling of lens systems also requires spectroscopic measurements of the redshift and velocity dispersions of the lens galaxy and extremely-high-precision measurements of the location of each image. This latter information will be best obtained by adaptive-optics integral field unit spectroscopy on large telescopes and ELTs (depending on the brightness of the sources involved).

Photometric redshift training spectroscopy for LSST: ELTs can also play a role in obtaining photometric redshift training/calibration spectroscopy for LSST. Although their comparatively small field of view and lower multiplexing compared to DESI or PFS limits the sample size and area that can be surveyed at one time, their huge light-gathering power helps to make up for it. As a result, ELTs could still play a role in photometric redshift training, as illustrated in Figure 4.4.3. Based upon their expected instrument characteristics, TMT and E-ELT would require more than 400 dark nights to conduct the baseline LSST training survey, but GMT with the MANIFEST fiber positioner could achieve this in fewer than 200. It is thus possible that ELTs could play a role in this work, potentially in concert with other facilities (e.g., obtaining infrared spectroscopy of objects that failed to yield redshifts in optical-only spectroscopy on smaller telescopes). An intermediate option would be provided by the FOBOS spectrograph on Keck, which could perform the LSST baseline survey in $\sim$ 300 dark nights, at substantially lower operating cost than an ELT.

Characterizing Galaxy Clusters: Clusters of galaxies are the most massive gravitationally bound structures in the universe. Their observed abundance and clustering properties as a function of their mass provides a sensitive probe of the growth of structure and, to a lesser degree, the expansion history of the universe. However, galaxy cluster abundance measurements from LSST will require additional data to mitigate systematic effects, in particular to enable an accurate calibration of the relationship between observable cluster properties and their total mass. Dedicated campaigns aimed at observing a fair subsample of galaxy clusters discovered by LSST using large telescopes and ELTs will facilitate precision cluster cosmology studies. By obtaining spectroscopy of many (dozens to 100) members within each of a set of individual clusters using modest-field-of-view multi-object spectrographs, the velocity dispersions and substructure within each cluster can be measured, providing measures of their mass and dynamical state. Spectroscopy in these fields can also help to assess the accuracy of and systematics that affect photometric redshifts in cluster fields. These studies are generally ill-suited to massively-multiplexed spectrographs on wide-field-of-view instruments, as their fiber density is too low to obtain spectra of many targets in a single galaxy cluster, but are better matched to the capabilities of existing large telescopes and the planned ELTs.

4.7 Opportunity: Rubin Observatory after LSST

The Vera C. Rubin Observatory will conduct its ten-year Legacy Survey of Space and Time (LSST) beginning c. 2024. At the conclusion of that period, the observatory will remain uniquely capable, with an etendue much larger than any current facility, and the potential to continue contribute to our understanding of cosmic acceleration via a number of possible pathways.

The simplest and least expensive option would be to simply continue to operate with the same instrumentation that will be used for LSST. In that case, the primary gains for cosmology would include the continuing stream of new transients (including type Ia supernovae) Rubin Observatory would discover, the deeper imaging obtained from longer surveys (though gaining only proportional to $\sqrt{t}$), and the potential to detect optical counterparts of gravitational wave sources through targeted follow-up imaging (for which the large collecting area and field of view of Rubin provide considerable advantages).

The next step up in complexity would be to use the LSST camera for a continuing survey, but with a different set of filters. In particular, if a set of filters offset from the LSST *ugrizy* filters by half their wavelength width were implemented, Rubin could double the amount of spectral information available for all targets by conducting a new 10-year survey, improving redshift accuracy for all objects (typically decreasing photometric redshift errors by 50% from the combination of greater spectral resolution and longer total observing time). This strategy would still maintain the same sensitivity that LSST will have for transient detection and gravitational wave source follow-up, enabling that work to continue.

One could further increase redshift accuracy by greatly increasing the total number of filters used to $\sim 20-30$ or more (and decreasing their wavelength width accordingly), effectively obtaining a low-resolution spectrum of all objects observed. This would be somewhat more expensive than the previous options due to the cost of Rubin filters, but could enable small redshift errors (of $\sim 0.005(1+z)$ or less, potentially reaching sufficient precision to obtain radial BAO information) if many-band observations were limited to a small subset ($< 10\%$) of the total LSST survey area. Surveys which cover the same sky area as Roman Space Telescope grism observations could be of particular interest, providing optical spectral information to complement the low-resolution infrared spectra from Roman. However, narrower filters would yield lower sensitivity to transients than LSST, limiting the science that Rubin could undertake in this scenario.

The most expensive option would be to develop an entirely new instrument to replace the LSST camera and install it at Rubin Observatory at the end of the LSST survey. With a new instrument Rubin Observatory could in principle be used for massively-multiplexed spectroscopy, though there would be significant engineering challenges involved; if a new spectroscopic facility is not going to be constructed by the mid-2030s, however, converting Rubin for spectroscopic use may still be the best choice.

Given that we do not yet know how Rubin Observatory and the LSST camera will perform, it is premature to select one of these options now. Instead, it would be prudent to evaluate the prospects for future science with the LSST camera as well as alternative opportunities after one to two years of LSST data have been obtained. By that time, the prospects for a new spectroscopic facility should also be better understood, which may affect this prioritization.

4.8 Opportunity: Research and Development for Future Experiments

4.8.1 Fiber positioners

The newest generation of high-multiplex spectrographs, including both DESI and the Subaru Prime Focus Spectrograph (PFS), use a set of robotically controlled motors to move optical fibers to the positions of the objects whose spectra will be measured; these are commonly referred to as “fiber positioners”. For such spectrographs, the multiplexing that can be achieved is limited by the total physical focal plane area in which light from objects of interest may be observed as well as by the size of each robotic fiber positioner; the smaller the positioners are, the more of them can fit within a given-size focal plane. The positioner size is typically characterized by the center-to-center distance between positioners, referred to as the pitch.

DESI has a fiber pitch of 10.4mm, as compared to 8mm for Subaru/PFS. These scales are primarily determined by the size of the motors used to position fibers. If smaller motors and positioners can be used, this would enable higher multiplexes within a given focal plane size, increasing the capabilities of any future spectroscopic facilities accordingly. Development of improved packaging methods and higher-reliability positioner motors would also be valuable, based upon DESI experience. In order to enable improved designs to be incorporated into the next generation of spectrographs, R & D to improve positioners should be a high priority in the short term.

4.8.2 CCD Detectors

Ground-based spectroscopic observations of faint astronomical sources in the low-signal, low-background regime are currently limited by detector readout noise. In particular, medium- to high-resolution spectroscopy at shorter wavelengths has low sky-background levels and significant gains can be achieved through reductions in readout noise ($\sim$0.5 e- rms/pix). Sub-electron noise would result in a $\sim$ 20% increase in survey speed, i.e., allowing a five year survey to achieve its goals in four years. Multi-object spectroscopic facilities are required to observe objects of widely varying brightness with the same fixed exposure time. Thus, the ability to control readout noise dynamically would allow photon counting when needed for faint sources, but will not waste time on bright sources that are shot-noise dominated. Skipper CCDs have an output readout stage that allows multiple non-destructive measurements of the charge packet in each pixel of the array thanks to its floating gate output sense node. This allows Skipper CCDs to achieve sub-electron readout noise over the entire detector area, or over specific sub-regions of the detector that are either pre-defined before the exposure or dynamically configured based on the first charge measurement in each pixel. Skipper CCDs are at a fairly mature stage of technical development, and are used in a wide range of particle physics experiments. The major hurdle when applying Skipper CCDs to future spectroscopic surveys comes from the increased readout time needed to perform multiple independent samples. Several avenues toward reducing the readout time of Skipper CCDs are being pursued at Fermilab and LBNL.

Silicon CCDs have matured for optical bands covering $3,600 < \lambda < 10,000\,\text{Å}$, but the effective band-gap around 1 eV limits their effectiveness at redder wavelengths. The primary spectroscopic feature used to determine redshift in galaxy surveys is due to forbidden transitions in singly-ionized oxygen ([OII]). These [OII] emission lines occur at 3,727 Å in the galaxy restframe, causing the signal to appear beyond the 10,000 Å cutoff in a silicon detector for galaxies at redshifts $z > 1.6$. Germanium CCDs can be processed with the same tools used to build silicon imaging devices, show promise for read noise and sensitivity comparable to that of silicon detectors, and offer a high quantum efficiency to wavelengths as red as 1.4 microns when cooled to 77 K. This increase in wavelength coverage will allow a spectroscopic identification of [OII] emission lines to $z = 2.6$, a factor of two increase in volume over what is accessible in the DESI galaxy sample. Fabrication of germanium CCDs faces several challenges that need to be addressed before these devices can be integrated onto large focal planes. Several processes in doping, etching, and film deposition are similar to those in silicon CCD fabrication, and may be compatible with current fabrication facilities. However, water solubility and low-temperature limitations result in the need for changes in gate-electrode technologies. In addition, there is only one wafer vendor in germanium and further investigation is required to ensure that purity requirements can be met at scale production on large wafers. Finally, germanium is higher density than silicon and requires a full assessment of handling and packaging techniques.

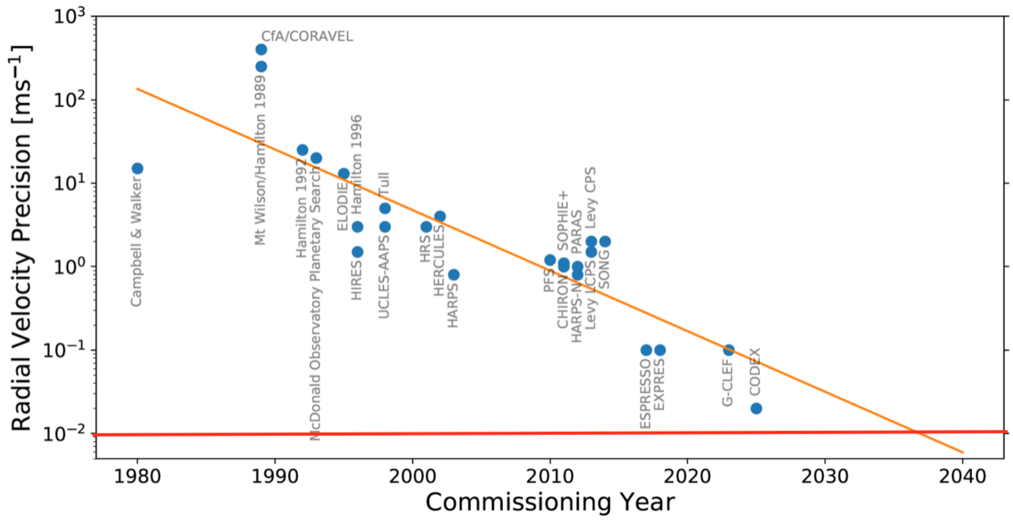

Figure 4-6 Improvements in RV precision for various upcoming instruments (adapted from Silverwood & Easther 2019 and taken from [62]). Cosmological redshift drift requires ~ 1 cm s^{-1} precision (red line) with stability of years to decades.

4.8.3 High Precision Spectroscopy

High precision spectroscopy has many uses in astronomy and has a long history in the area of exo-planet finding and more recentlty in the understanding of dark matter dynamics in the Miky Way Halo as traced by the velocities and accelerations of stars. Its relevance to this group is a tantalizing possibility of measuring the expansion of the universe *directly* by observing the average redshift of objects increasing with time. The size of this effect is redshift dependent and is around $\Delta\lambda/\lambda \sim 10^{-10}$ per year. The current start of the art in precision spectroscopy is approaching the required levels of precision and instrument stability to enable such measurements, especially with the externally dispersed interferometric (EDI) spectroscopy [62]. This technique would offer a potentially very clean direct probe of Hubble's constant enabling a potential resolution of the Hubble parameter tension. Long term it would also enable a unique probe of the cosmological constant and other consituents of the Universe. In Figure 4-6 we show that based on the historical rate of precision improvements we expect the neccessary precision to detect cosmological drift will be reached over the next two decades.

4.8.4 High Precision Astrometry

Similar to high precision astronomy, the high precision astrometry also has potential to enable a potentially transformative new cosmological probes. These include, in conjuction with the high precision spectroscopy, a full 3D mapping of movement of stars in our own galaxy, thus an even more complete probe of dark matter through studying the Milky Way dynamics. More relevant for cosmological studies are the secular astropmetric motions of distant quasars. These undergo both the apparent movements due to cosmological parallax that can be further boosted for strongly lensed quasars as the precise line of sight moves through time [62]. At similar order of magnitude, there are also true astrometric movements towards over-densities that could in principle be observed through cross-correlation of density tracers. These effects could be detected by plannint next generation facilities in Radio (ngVLA) as well as optical with the upcoming generation of extremely large telescopes. On the instrumentation front, new dedicated techniques are appearing, employing quanty assisted astrometry techniques. These have strong synergies with the existing DOE investments into quantum technologies.

4.8.5 Intensity mapping

Intensity mapping is an orthogonal approach to performing cosmological survey science by insutrumentation that gives us ability to isolate individual objects as in traditional galaxy surevys and instead focuses on variations in aggregate intensity from many objects. This aggregate intensity varies across the sky, tracing the fluctuations in the underlying dark matter densities that in turns modulates the local number density of galaxies.

It is used mostly for surveys at low frequencies where the limiting factor is the resolution of the instrument, but it can also be used to work with objects that are below the detections threshold of a given survey. We briefly overview the three main experimental efforts in this area:

4.8.5.1 21 cm intensity mapping

The 21 cm spin-flip transition in the neutral hydrogen is an ideal target for intensity mapping. Neutral hydrogen is present in all galaxies and can be observed using appropriately optimized radio instruments. The advances in off-the-shelf radio-frequency instrumentation driven by the needs of the wireless industry has enabled extremely cost-effective interferometric radio telescopes that could revolutionize the survey cosmology. The effect has been recently demonstrated in cross-correlation by CHIME [63] and MeerKAT [64].

DOE has developed a PUMA proposal [65] for the next generation cosmology survey that has been submitted for consideration by the Decadal Survey [66]. The CF04 invited whitepaper [7] has shown that it would enable unprecedent accuracy in measuring the expansion history and cosmological parameters accross cosmic ages as shown in Figures 4-2.

[**AS**: (add a plot)].

However, the technique is far from being ready and there exist a credibility gap between the PUMA promise and the scientific reach of the current generation of experiments. This credibility gap can be traversed by small injection into R&D as a investment into the long future. This funding can be applied along two independent and largely orthogonal axes as outlined in PUMA letter of interest (see also [66]). First, as a part of long term strategy, it is important to maximize the scientific return on investment from the current generation of precursor experiments, many of which suffer from under-staffing of the science effort. A strategic investment by DOE to enter in collaboration with one of the current generation experiments with the specific goal of contributing to the simulation and analysis effort would be a well suited to the DOE institutional strength. On the other hand, it is clear that this field would benefit from development of low cost and low energy consumption hardware that forms the generic building blocks of RF infrastructure: digital channelizes, correlators and spectrometers. This developments additionally have significant overlap with instrumentation development for light sources and particle accelerators.

4.8.5.2 Intensity mapping in sub-mm

Every galaxy in the universe contains various amounts of dust, which absorbs much of the stellar optical light and re-emitts in the intfra-red (IR). Rest-frame far-IR lines such as the CO rotational transitions and the [CII] fine-structure line can also be used for intensity mapping at millimeter wavelengths between 10 and 600GHz [67, 68]. These lines are bright and have been detected in individual galaxies out to $z \sim 7$.

This frequency band coincides with the bands where CMB experiments operate. The intensity mapping experiments at these wavelengths are therefore intrinsically similar to CMB experiments, but instead of broadband bolometers they use spectrometers. Analog on-chip spectrometers have been under development for some time and are reaching maturity to start pathfinder deployments. One of the main advantages of this techqniues is that it can profitably re-use much of the already developed CMB infrastructure, including existing telescopes and developed observatories as well as know-how and infrastructure in developing cryogenic detectors. This community needs further targeted investment in developing on-chip spectrometer with competitive frequency resolution, detector densities, multiplexing and noise performance.

4.8.5.3 Intensity mapping in optical

Finally, intensity mapping can in principle also be performed in optical, in particular with the most abundant Lyman-α and H-α lines. Since we do not have large-scale imagers with the spectral sensitivity, this cannot be naturally done with the upcoming generation of optical experiments. However, it is possible to extract signal though subtle data analysis. For example, looking for a secondary signal under target galaxy spectra with DESI or cross-correlating field intensity with other tracers with the LSST are both plausible path-finder techniques that require modest investment of research funding with no change in hardware and even survey strategy.

4.9 Conclusion

As we have described, projects at a wide variety of scales can help us to make progress on both investigating the nature of cosmic acceleration and investigating other cosmological phenomena simultaneously. Given the richness of the datasets that they would provide, the many unique cosmological probes that they would enable, a Stage V spectroscopic facility represents the greatest opportunity to advance our understanding; such a facility would simultaneously provide new probes of the nature of dark matter, as described in Chapter 3 of this report. However, there exist other smaller-scale opportunities to enhance our understanding that can be undertaken in the near term, including smaller-scale spectroscopic surveys with the DESI instrument, and efforts to obtain complementary data to enhance the cosmological constraining power of LSST. These short-term projects should be counterbalanced by an active research and development effort to explore new techniques and instrumentation concepts that could enable novel cosmological experiments that would begin operation in the later 2030s or beyond. The Vera C. Rubin Observatory similarly could enable new opportunities to make progress once LSST is completed, though the time is not yet ripe to evaluate the possibilities.

A balanced portfolio of efforts should simultaneously enable us to enhance our understanding of cosmic acceleration, including both tests of dark energy models and modifications to GR; provide strong constraints on the sum of neutrino masses; probe the origins of cosmic inflation by testing for non-Gaussianity and features in the primordial power spectrum; test for the presence of dark energy-like components in early phases of the Universe's history; and help to resolve current tensions in measurements of the Hubble parameter and the amplitude of matter density fluctuations. The modern universe is rich in cosmological information; it will be up to us to take advantage of the opportunities to improve our understanding of fundamental physics that it can provide.

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