Snowmass2021 - Letter of Interest

Deep Multi-object Spectroscopy to Enhance Dark Energy Science from LSST

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract: Access to deep ($i \sim 25$), highly-multiplexed optical and near-infrared multi-object spectroscopy (MOS) on 8–40m telescopes would greatly improve measurements of cosmological parameters from the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST). The largest gain would come from improvements to LSST photometric redshifts, which are employed directly or indirectly for every major LSST cosmological probe. Deep spectroscopic datasets will enable reduced uncertainties in the redshifts of individual objects via optimized training. The resulting data will also constrain the impact of blending on photo-z's. Focused spectroscopic campaigns can also improve weak lensing cosmology by constraining the intrinsic alignments between the orientations of galaxies. Galaxy cluster studies can be enhanced by measuring motions of galaxies in and around clusters and by testing photo-z performance in regions of high surface density. Photometric redshift and intrinsic alignment studies are best-suited to instruments on large-aperture telescopes with wider fields of view (e.g., Subaru/PFS, MSE, Keck/FOBOS or GMT/MANIFEST), but cluster investigations can be pursued with smaller-field instruments (e.g., Gemini/GMOS, Keck/DEIMOS, or TMT/WFOS). Large numbers of telescope-nights will be needed to accomplish all of these goals.

Introduction: The Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST) will greatly increase our knowledge of cosmology over the years 2023–2033, constraining fundamental cosmological parameters using multiple complementary methods. However, the dark energy analyses that will be carried out by the LSST Dark Energy Science Collaboration (DESC) will only be able to reach the full potential of Rubin if additional data from other ground-based facilities to improve photometric redshift estimates and reduce systematic uncertainties is available[1].

In this Letter of Interest, we summarize the science opportunities to enhance cosmological measurements from LSST that would be enabled by access to **deep** ($i \sim 25$)**, highly-multiplexed** optical and near-infrared multi-object spectroscopy on 8–40m telescopes. Every cosmological probe that DESC plans to apply to Rubin data would benefit from these capabilities. More details are provided in a companion white paper submitted to the Astro2020 process[2], available at https://arxiv.org/abs/1903.09325.

Deep Spectroscopic Samples for Photo-z Training: Photometric redshifts are critical for all LSST probes of cosmology. Even in cases where follow-up spectroscopy of individual objects will be needed photo-z's are used to identify targets of interest. However, if photometric redshift estimates are systematically biased, dark energy inference can be catastrophically biased as well (see, e.g.,[3]); as a result photo-z's are both a critical tool and a major source of concern affecting all cosmological analyses. The great depth of LSST data makes the required spectroscopy for this difficult.

Lacking a comprehensive knowledge of galaxy evolution, the only way in which photo-z errors can be reduced and biases characterized is via galaxies with robust spectroscopic redshift measurements. Photometric redshift methods that are trained from larger and more complete spectroscopic samples greatly improve the constraining power of LSST, for example by providing sharper maps of the large-scale structure and improved clustering statistics, yielding better photometric classifications for supernovae, enabling identification of lower-mass galaxy clusters at higher confidence, and providing better intrinsic alignment mitigation for weak lensing measurements. If photo-z's are limited only by photometric errors (as with a perfect training set), LSST can deliver photo-z estimates with sub-2$\%$ uncertainties ($\sigma_z < 0.02(1+z)$), but errors in real LSST-depth data sets with our current knowledge of galaxy spectral energy distributions are closer to 5$\%$. Achieving the ideal performance by having a large training sample spanning the properties of objects used for cosmology would improve the Dark Energy Task Force Figure of Merit from LSST lensing and Baryon Acoustic Oscillations alone by $\sim 40\%$[4;5].

To improve photometric redshift accuracy and characterize error distributions at the required fidelity, we need sets of galaxies for which the true z is securely known. If spec-z's could be obtained for a large, unbiased sample of objects, both needs can be fulfilled using the same data. In a recent paper[6], it was concluded that an effective training set of photometric redshifts for the LSST weak lensing sample would require highly-multiplexed medium-resolution ($R \sim 4000$) spectroscopy covering as much of the optical/infrared window as possible with very long exposure times on large telescopes. To enable photo-z direct calibration errors to be subdominant to other uncertainties if the training set were used for that purpose, the spec-z sample must comprise at least 20,000 galaxies spanning the full color and magnitude range used for cosmological studies, reaching $i = 25$; as can be seen in Fig. 1 of[2], improvements in photo-z errors and outlier rates are slow for larger samples than this.

To both quantify and mitigate the effects of sample/cosmic variance[7], the survey strategy described in Ref.[6] seeks to obtain spectroscopy spanning at least 15 widely-separated fields a minimum of $20'$ in diameter. Such a survey has comparable sample/cosmic variance to the Euclid C3R2 strategy of six 1 sq. deg. fields[8], but requires only $\sim 22\%$ as much sky area to be covered. Estimates of the amount of dark time required for such a survey (assuming one-third losses for weather and overheads) for a variety of instruments and telescopes of varying characteristics, updated from the tables in Ref.[6], are summarized online at http://d-scholarship.pitt.edu/id/eprint/36036.

Testing the Impact of Blending on Photometric Redshifts: Due to its unprecedented depth and sensitivity to the low-surface-brightness outer regions of galaxies, the probability of a given object overlapping with others is $> 60\%$[9;10]. These overlaps complicate the measurement of galaxy fluxes and shapes[11;12] and can bias individual-object photo-z's and estimates of overall redshift distributions[13]. Deep multi-object, medium-resolution spectroscopy can detect the presence of blends and the redshifts of each component by identifying superimposed features in a spectrum. As a result, the proposed photometric redshift training spectroscopy should also greatly enhance studies of blending in LSST data.

Constraining Models of Intrinsic Galaxy Alignments Intrinsic correlations between galaxy shapes ("intrinsic alignments" or IA) induced by local/environmental effects are an important contaminant to weak lensing measurements biasing the cosmological information inferred from it[14]. By enabling the 3D localization of galaxies, a deep MOS campaign would provide greatly-improved direct constraints on intrinsic alignments for typical weak lensing sources, rather than only for the bright and nearby objects which current datasets constrain[9;15;16]. Such data would extend our knowledge of IA to unexplored regimes, resolve the current inconsistencies between predictions of different hydrodynamical simulations[17–19], and allow better priors to be placed on IA parameters, increasing the cosmological constraining power of LSST. Ideally this would be done with a dense sample of $> 10^5$ objects down to the LSST weak lensing magnitude limit. If this is not possible, swapping targeting amongst brighter galaxies during a photo-z training survey would allow the requisite sample size to be attained and IA models to be tested and optimized, even if the faint limit is not reached.

Enhancing Cluster Cosmology via Spectroscopy: Deep MOS of galaxies in a set of fields containing galaxy clusters will improve LSST cluster cosmology by training and testing photo-z's in the cluster regime, where they may be degraded due to the differing galaxy populations of clusters vs. the field, magnification and reddening of background sources, and severe blending due to cluster galaxies[20–22]. For this, it would be desirable to obtain spectroscopy down to weak lensing depths for a sample of ~ 20 clusters spanning a range of redshifts. This is best achieved with high-throughput, high-multiplex spectrographs with FOVs of $\sim 10'$ (wide-format IFUs may be suitable in cluster cores), as detailed in[2].

Deep MOS observations in the fields of clusters will also enable direct mass estimates for galaxy clusters via the infall method[23–26], providing an additional calibration of the mass-richness relation[27] "for free" from the photometric redshift training/test spectroscopy. In conjunction with weak-lensing measurements, this will enable a sensitive test of modified gravity theories e.g.,[28].

Recommendations

Given the large gains to LSST cosmological studies that will come from deep multi-object spectroscopy, we recommend that access to modestly-wide-field, highly-multiplexed, large aperture spectroscopic facilities be pursued during the next decade. Specifically,

- For photometric redshift training and tests of blending and intrinsic alignment effects, large time allocations on an instrument with maximal multiplexing and a field of view of at least $20'$ diameter are needed, preferably on a > 6m telescope to limit total survey duration and hence personnel costs.[1]
- For galaxy cluster studies, targeting more densely-packed objects over smaller fields of view is desirable, allowing large telescopes with limited FOV to contribute to this science.

[1]See http://d-scholarship.pitt.edu/id/eprint/36036 for survey time estimates for various instrument/telescope combinations.

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