Snowmass2021 - Letter of Interest

Wide-field 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: Data from wide-field (> 20 deg^2 total survey area), highly-multiplexed optical and near-infrared multi-object spectroscopy on 4–15m telescopes would help the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST) its full potential. This could come in the form of new large surveys and/or adding additional targets to already-planned projects. Photometric redshifts can be calibrated with high precision using cross-correlations of LSST objects against spectroscopic samples that span thousands of square degrees. Cross-correlations of faint LSST galaxies or lensing maps with spectroscopic samples can constrain intrinsic alignment systematics and provide new tests of modified gravity theories. Large numbers of LSST strong lens systems and supernovae can be studied efficiently by piggybacking on large-area spectroscopic surveys. Finally, redshifts can be measured for a high fraction of the supernovae in the Rubin Deep Drilling Fields (DDFs) by targeting their hosts with wide-field spectrographs. For wide-area surveys, DESI or MSE in the northern portion of the LSST footprint or 4MOST in the south would be good options; DESI, 4MOST, Subaru/PFS, or MSE would be well-suited for DDF surveys. The most efficient solution would be a new wide-field, highly-multiplexed spectroscopic instrument in the southern hemisphere with > 6m aperture.

Introduction: The The Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST;[1;2]) will transform our knowledge of cosmology over the years 2023–2033, constraining fundamental cosmological physics using a variety of probes. 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 reduce systematic uncertainties is available[3].

In this Letter of Interest, we summarize how community access to **wide-field** ($>$ 20 **deg**^{2} **total survey area), highly-multiplexed** optical and near-infrared multi-object spectroscopy (MOS) on 4–15m telescopes can increase the return from the LSST dataset and unlock additional scientific opportunities for every major cosmological probe. More details are provided in a companion white paper submitted to the Astro2020 process[4], available at https://arxiv.org/pdf/1903.09323.pdf.

Photo-z Calibration via Spectroscopic Cross-Correlations: Photometric redshifts (photo-z's) are a critical tool for DESC. If photo-z estimates have an undetected systematic bias, dark energy inference can be catastrophically affected (see, e.g.,[3;5]). Photo-z calibration requirements for DESC are thus extremely stringent. Direct calibration via a large, representative spec-z sample may not be possible given the depth of LSST[6]. However, methods based upon cross-correlating the locations of LSST galaxies with spec-z samples can provide an alternative route for photo-z calibration[7], so long as spectroscopic samples span the redshift range of the LSST objects and cover a wide area of sky.

The DESI[8] and 4MOST[9] surveys will provide sufficiently large samples of galaxy and quasar redshifts, but mostly in the Northern part of the LSST footprint. There is a significant risk that LSST photometry – and hence photo-z's – may be systematically different in this region due to differences in typical observing conditions. It would thus be valuable to enlarge the samples available for cross-correlation calibration over Southern regions not covered by these surveys.

Characterizing Intrinsic Alignments via Cross-Correlations Intrinsic correlations between shapes of galaxies that are physically near each other ("intrinsic alignments" or IA) are a known contaminant to weak gravitational lensing (WL)[10;11]. If not accounted for, their presence can generate significant biases in cosmological WL analyses[12–15]. Wide-field MOS can measure the cross-correlation between positions of bright galaxies with spectroscopy and intrinsic shapes of fainter galaxies used for lensing, constraining IA models[16–18]. Cross-correlations with larger samples than those from by DESI and 4MOST overlap over wider areas would yield better constraints on IA models, improving S/N in IA measurements by up to $\sim 2\times$.

Testing General Relativity on Cosmological Scales: Combining cross-correlations between galaxy density and lensing with measurements of redshift-space distortions in galaxy clustering allows for tests of gravity on cosmological scales[19]. A sample of galaxies with spec-z's that overlaps the LSST WL sample would enable measurement of the E_G statistic[20;21]. The DESI and 4MOST galaxy samples should enable multiple determinations of E_G to ~ 0.004, roughly 10 times more precise than current constraints. Enlarging the northern LSST footprint (cf.[22]) would reduce errors by $\sim 25\%$ more; greater improvements are possible with enlarged southern spectroscopic samples.

Characterizing Strong Lensing Systems from Rubin: LSST will discover $\sim 100,000$ strong gravitational lenses[23], 100 times more than are currently known. Strong lensing science requires redshifts for both lens and source. Many lenses are bright enough for redshift measurements via targeted fibers within very wide-area surveys, enabling identification of the systems best suited for follow-up observations as described in[24].

Spectroscopy for Supernova Cosmology: Type Ia supernovae (SNe Ia) provide a mature probe of the accelerating universe (e.g.,[25]), and their use as standardizable candles is an immediate route to measuring the equation of state of dark energy. However, a major systematic uncertainty will be the photometric classification and redshift measurement of the supernovae found. Wide-field spectroscopy can address this by exploiting the fact that wherever a follow-up facility points in the extragalactic sky, there will be known time-variable sources, including both recently discovered transients and older, now-faded events.

Spectroscopy will serve two major goals. The first is the classification of live SNe and the construction of the optimized, large, homogeneous and representative training sets needed for purely photometric classifiers that may be used for the next generation of SN Ia cosmology [26]. The second goal is to obtain spectroscopic redshifts for host galaxies of SNe that have faded away. While conventional SNIa cosmology analyses rely on spectroscopic follow-up of live SNe, new analyses e.g., [27–29] show that it is possible to take advantage of even larger samples of SNe after obtaining spec-z's of their host galaxies.

Supernovae and their Hosts in LSST Deep Drilling Fields Due to the higher-quality light curves provided by more frequent and deeper photometry, the best-characterized LSST SN samples will come from the DDFs. Due to the comparatively small area covered by these fields (~ 50 deg^2 total) and the low surface density of SNe, it is feasible to obtain long exposures on all DDF live supernovae or their hosts using wide-field spectrographs (e.g., DESI or Subaru/PFS in the North and 4MOST in the South); c.f. [30]. In addition to the cosmological measurements directly enabled by DDF SN and host redshifts, the resulting dataset should provide a wealth of training data for photometric classification of transients, as well as high S/N light curve templates for other supernovae that have only LSST data.

Supernovae and their Hosts in the Wide, Fast, Deep (WFD) Survey While the smaller area of the deep fields ensures that host redshifts can be obtained for a higher fraction of all supernova hosts than in the WFD, the wider LSST coverage will yield a much larger number of supernovae in total. This sample of hundreds of thousands of SNe will revolutionize cosmological analyses and enable extensive studies of systematics (cf. Figure 1 of [4]). The 4MOST/TIDES program will target supernovae and their hosts for spectroscopy across the WFD footprint, but will only run for the first half of the LSST survey [31]. Additional spectroscopic resources will be needed in the later years of LSST to maximize the impact of the survey.

The distribution of supernova host redshift measurements will depend on the allocation of spectroscopic resources from ground-based telescopes. In [4] we have tested the impact on the Dark Energy Task Force Figure of Merit (FoM) from altering the fiducial redshift efficiencies from [3]. From these tests we find that the DETF FoM is most sensitive to the number of supernovae at high redshift, and hence reductions in the time allocated to the DDFs have the greatest effect.

Recommendations: Rubin cosmological constraints can be significantly improved by additional wide-field spectroscopy of several types. For example,

- Increasing the area in the southern hemisphere with DESI-like selection of galaxies and quasars would improve a broad range of cross-correlation science. This could be achieved by performing additional surveys with the 4MOST instrument.
- Denser and/or higher-redshift sampling of galaxies over thousands of square degrees would improve constraints on theories of modified gravity and models of intrinsic alignments; this could be done efficiently with DESI, MegaMapper, Subaru/PFS, or the Maunakea Spectroscopic Explorer.
- Spectroscopic follow-up for strong lens systems and SNe/hosts will still be needed after 4MOST/TiDES observations are finished in 2027 [31]. This could be pursued via an extension of the 4MOST survey or by using PFS (for DDFs), DESI, or MSE in the portions of the LSST footprint they reach. [1]
- The optimal solution for wide-field spectroscopy spanning the full Rubin footprint would be a highly-multiplexed, wide field-of-view instrument in the South on an aperture of at least 6.5m diameter. No such capability currently exists, but it would significantly increase the HEP impact of Rubin.

[1] Total observing times needed to complete the DDF supernova host survey are described in [30] and provided at http://d-scholarship.pitt.edu/id/eprint/36041.

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References

[1] Željko Ivezić, Steven M. Kahn, J. Anthony Tyson, *et al.* LSST: from Science Drivers to Reference Design and Anticipated Data Products. *arXiv e-prints*, page arXiv:0805.2366, May 2008.

[2] LSST Science Collaboration, Paul A. Abell, Julius Allison, *et al.* LSST Science Book, Version 2.0. *arXiv e-prints*, page arXiv:0912.0201, Dec 2009.

[3] The LSST Dark Energy Science Collaboration, R. Mandelbaum, T. Eifler, *et al.* The LSST Dark Energy Science Collaboration (DESC) Science Requirements Document. *arXiv e-prints*, page arXiv:1809.01669, September 2018.

[4] R. Mandelbaum *et al.* Wide-field Multi-Object Spectroscopy to Enhance Dark Energy Science from LSST. *Astro2020 White Paper*, 2019.

[5] A. P. Hearin, A. R. Zentner, Z. Ma, and D. Huterer. A General Study of the Influence of Catastrophic Photometric Redshift Errors on Cosmology with Cosmic Shear Tomography. *ApJ*, 720:1351–1369, September 2010.

[6] J. A. Newman, A. Abate, F. B. Abdalla, *et al.* Spectroscopic needs for imaging dark energy experiments. *Astroparticle Physics*, 63:81–100, March 2015.

[7] J. A. Newman. Calibrating Redshift Distributions beyond Spectroscopic Limits with Cross-Correlations. *ApJ*, 684:88–101, September 2008.

[8] DESI Collaboration, Amir Aghamousa, Jessica Aguilar, *et al.* The DESI Experiment Part I: Science,Targeting, and Survey Design. *arXiv e-prints*, page arXiv:1611.00036, Oct 2016.

[9] R. S. de Jong, O. Agertz, A. Agudo Berbel, *et al.* 4MOST: Project overview and information for the First Call for Proposals. *arXiv e-prints*, page arXiv:1903.02464, Mar 2019.

[10] M. L. Brown, A. N. Taylor, N. C. Hambly, and S. Dye. Measurement of intrinsic alignments in galaxy ellipticities. *MNRAS*, 333:501–509, July 2002.

[11] M. A. Troxel and Mustapha Ishak. The intrinsic alignment of galaxies and its impact on weak gravitational lensing in an era of precision cosmology. *Phys. Rep.*, 558:1–59, February 2015.

[12] D. Kirk, A. Rassat, O. Host, and S. Bridle. The cosmological impact of intrinsic alignment model choice for cosmic shear. *MNRAS*, 424:1647–1657, August 2012.

[13] Elisabeth Krause, Tim Eifler, and Jonathan Blazek. The impact of intrinsic alignment on current and future cosmic shear surveys. *MNRAS*, 456:207–222, February 2016.

[14] J. Blazek, N. MacCrann, M. A. Troxel, and X. Fang. Beyond linear galaxy alignments. *arXiv e-prints*, page arXiv:1708.09247, August 2017.

[15] Ji Yao, Mustapha Ishak, Weikang Lin, and Michael Troxel. Effects of self-calibration of intrinsic alignment on cosmological parameter constraints from future cosmic shear surveys. *J. Cosmology Astropart. Phys.*, 2017(10):056, October 2017.

[16] N. E. Chisari, R. Mandelbaum, M. A. Strauss, E. M. Huff, and N. A. Bahcall. Intrinsic alignments of group and cluster galaxies in photometric surveys. *MNRAS*, 445:726–748, November 2014.

[17] S. Singh, R. Mandelbaum, and S. More. Intrinsic alignments of SDSS-III BOSS LOWZ sample galaxies. *MNRAS*, 450:2195–2216, June 2015.

[18] Harry Johnston, Christos Georgiou, Benjamin Joachimi, *et al.* KiDS+GAMA: Intrinsic alignment model constraints for current and future weak lensing cosmology. *arXiv e-prints*, page arXiv:1811.09598, November 2018.

[19] Mustapha Ishak. Testing general relativity in cosmology. *Living Reviews in Relativity*, 22:1, December 2019.

[20] R. Reyes, R. Mandelbaum, U. Seljak, *et al.* Confirmation of general relativity on large scales from weak lensing and galaxy velocities. *Nature*, 464:256–258, March 2010.

[21] P. Zhang, M. Liguori, R. Bean, and S. Dodelson. Probing Gravity at Cosmological Scales by Measurements which Test the Relationship between Gravitational Lensing and Matter Overdensity. *Physical Review Letters*, 99(14):141302, October 2007.

[22] Knut Olsen, Marcella Di Criscienzo, R. Lynne Jones, *et al.* A Big Sky Approach to Cadence Diplomacy. *arXiv e-prints*, page arXiv:1812.02204, Dec 2018.

[23] T. E. Collett. The Population of Galaxy-Galaxy Strong Lenses in Forthcoming Optical Imaging Surveys. *ApJ*, 811:20, September 2015.

[24] R. Hlozek *et al.* Single-object Imaging and Spectroscopy to Enhance Dark Energy Science from LSST. *Astro2020 White Paper*, 2019.

[25] DES Collaboration, T. M. C. Abbott, S. Allam, *et al.* First Cosmology Results using Type Ia Supernovae from the Dark Energy Survey: Constraints on Cosmological Parameters. *arXiv e-prints*, page arXiv:1811.02374, Nov 2018.

[26] M. Lochner, J. D. McEwen, H. V. Peiris, O. Lahav, and M. K. Winter. Photometric Supernova Classification with Machine Learning. *ApJS*, 225:31, August 2016.

[27] D. O. Jones, D. M. Scolnic, A. G. Riess, *et al.* Measuring Dark Energy Properties with Photometrically Classified Pan-STARRS Supernovae. II. Cosmological Parameters. *ApJ*, 857:51, Apr 2018.

[28] Heather Campbell, Chris B. D'Andrea, Robert C. Nichol, *et al.* Cosmology with Photometrically Classified Type Ia Supernovae from the SDSS-II Supernova Survey. *ApJ*, 763:88, Feb 2013.

[29] Renée Hlozek, Martin Kunz, Bruce Bassett, *et al.* Photometric Supernova Cosmology with BEAMS and SDSS-II. *ApJ*, 752:79, Jun 2012.

[30] J. Najita, B. Willman, D. P. Finkbeiner, *et al.* Maximizing Science in the Era of LSST: A Community-Based Study of Needed US Capabilities. *arXiv e-prints*, page arXiv:1610.01661, October 2016.

[31] E. Swann, M. Sullivan, J. Carrick, *et al.* 4MOST Consortium Survey 10: The Time-Domain Extragalactic Survey (TiDES). *arXiv e-prints*, page arXiv:1903.02476, Mar 2019.