Snowmass2021 - Letter of Interest

Single-object Imaging and Spectroscopy to Enhance Dark Energy Science from Rubin Observatory's 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]*

Contact Information: (authors listed after the text)
Submitter Name/Institution: Renée Hložek, University of Toronto, Dunlap Institute for Astronomy and Astrophysics
Collaboration: LSST Dark Energy Science Collaboration (LSST DESC)
Contact Email: hlozek@dunlap.utoronto.ca

Abstract: Single-object imaging and spectroscopy on telescopes with apertures ranging from $\sim$ 4m to 40m have the potential to greatly enhance the cosmological constraints that can be obtained from the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST). Two major cosmological probes will benefit greatly from single-target follow-up. Accurate spectrophotometry for nearby and distant Type Ia supernovae will expand the cosmological distance lever arm by unlocking the constraining power of high-z supernovae. Furthermore, cosmology with time delays of strongly-lensed supernovae and quasars will require additional high-cadence imaging to supplement LSST, adaptive optics imaging or spectroscopy for accurate lens and source positions, and IFU or slit spectroscopy to measure detailed properties of lens systems. For both science cases, LSST will deliver a large sample of the objects of interest, but additional data to characterize both individual systems and overall systematics will be key to ensuring robust cosmological inference to high redshifts. Community access to large amounts of natural-seeing imaging on $\sim$2–4m telescopes, adaptive optics imaging and spectroscopy on 8–40m telescopes, and high-throughput single-target spectroscopy on 4–40m telescopes will be necessary for LSST time domain cosmology to reach its full potential.

Introduction: The Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) will play a major role in improving our knowledge of cosmology over the years 2023–2033 via both wide-area and deep surveys. However, obtaining measurements that extract the full potential of LSST will require additional data from other ground-based facilities.

In this Letter of Interest, we summarize the science opportunities to build on and strengthen the LSST dataset that would be made possible by community access to telescopes and instruments enabling detailed follow-up of individual objects. More details are provided in a companion white paper submitted to the Astro2020 process[1], available at https://arxiv.org/abs/1903.09324.

Type Ia Supernova Spectroscopy to High Redshifts: As described in a companion paper[2], the largest sets of redshift measurements for LSST supernovae should come from targeting SNe and their host galaxies via wide-field multi-object spectroscopy, either using a small fraction of fibers in surveys that span the LSST footprint or via targeted surveys in the LSST Deep Drilling Fields (DDFs). However, higher signal-to-noise observations will be needed for a significant sample of low-z SNe to characterize the intrinsic range of SN spectra. Spectroscopy for samples of high-z LSST Type Ia SN ($z \sim 0.5 - 1.4$) are also needed; this will require targeted long-exposure follow-up while they are still bright.

Much work has gone into developing methods for determining supernova types and redshifts from photometry alone, but this can be difficult when applied over a large redshift range. Current photometric identification techniques require spectroscopically classified training samples, ideally over the full range of redshifts under consideration. Detailed spectrophotometric studies of low-z Type Ia SN will be the best source of high-signal-to-noise information about the behavior over a large range of Type Ia SN subtypes, which can make smaller telescopes useful for this work. However, fully characterizing some classes of objects from LSST at the faintest magnitudes – e.g., SLSN and Type II SN, as in[3;4] – will require spectroscopic observations on 25–40 m class telescopes.

Detailed understanding of a variety of potential sources of systematic error will be crucial for supernova science with LSST, including evolution of the Type Ia SN population with redshift; errors in the specification of the spectral energy distribution (SED) in different redshift/rest-frame wavelength ranges that can affect training of light curve models; and mis-identifications of fine sub-types of Type Ia supernovae (used to find "twin" SNe as in[5]). Very high quality spectra of "live" supernovae are needed if they are to be used to study these subtle effects. For systematics constraints on measurements of high-redshift Type Ia SN to be commensurate with the tight statistical uncertainties resulting from the LSST sample sizes, there will be a need for new instrumentation for ground-based telescopes (e.g., IFU or high-throughput spectrographs now in the planning stages for 2–4 m telescopes and IFU reformatters on existing spectrographs (with or without AO) on 8–40 m telescopes). Space-based observations with *Euclid*, the *Roman Space Telescope*, or other proposed missions could also contribute to this effort.

Cosmology with Strong Gravitational Lens Systems: The multiple images of strongly gravitationally lensed sources arrive at different times because they travel different paths and through different gravitational potentials to reach us[6;7]. When a strongly lensed source is time variable, the arrival time delays can be measured and combined with a mass model to provide an estimate of cosmological parameters.

Time delays from lensed supernovae present opportunities to observe the earliest phases of supernova explosions (helping in the development of physical models of the events); to infer cosmological parameters; and to map substructure in lens galaxies. However, in-depth studies of large numbers of systems are needed to achieve these goals. Thanks to novel lensed-supernova hunting techniques, a new generation of alert-based wide-field imaging surveys like LSST will yield thousands of new events[8]. This vast increase in sample size will enable groundbreaking new measurements with the potential to rapidly deliver precision constraints on the Hubble parameter (H_0) and dark energy. The Hubble constant has been determined with high precision via measurements in the *nearby* universe using the distance ladder[9] yielding $\mathrm{H_0} = 73.24 \pm 1.74$ km/s/Mpc. It has also been determined via studies of the *primordial* universe using the cosmic microwave background (CMB),[10] obtaining $\mathrm{H_0} = 66.93 \pm 0.62$ km/s/Mpc when an ΛCDM cosmology is assumed. The local and distant measurements disagree by 3.8σ. This is potentially a sign of new fundamental physics, such as sterile neutrinos or "phantom" dark energy e.g.,[11–13], but could also be a sign of systematics in the measurements e.g.,[14;15]. A robust, accurate, and precise measurement of $\mathrm{H_0}$ would break degeneracies in other cosmological measurements and improve a variety of constraints on parameters of interest.

The projected constraint on $\mathrm{H_0}$ from the ~ 100 strongly lensed supernovae LSST will discover is comparable in precision to the leading current measurement from the combination of *Planck* and BOSS data[16;17], as shown in Fig. 2 of[1]. It is estimated that LSST will also find 10^4 lensed quasars of which around 100 will be viable time-delay systems[18]. Time delays from supernovae and quasars are sensitive to dark energy in a completely different way than cosmological probes based on distances and volumes (e.g., the CMB, the Type Ia SN distance-redshift relation, and BAO)[19;20], making them highly complementary to other methods.

To measure time delays, high-cadence, high-resolution, multi-filter imaging of spatially-resolved lensed images is required. In general, the LSST cadence may be insufficient for this purpose. As a result, dedicated follow-up imaging of lens systems with more frequent visits will be needed, but this can often be performed on smaller telescopes (2–4 m). To model the lens systems, both the source and lens redshifts are required, as well as high-resolution imaging of the lens galaxy and lensed host galaxy to measure apparent positions with high precision. Kinematic velocity dispersions derived from lens galaxy spectra can also improve the models. Adaptive optics (AO) IFU spectroscopy on 8–40m-class telescopes (with aperture required depending on brightness) can satisfy all of these needs simultaneously, but the combination of AO imaging with slit spectroscopy would also suffice.

Recommendations: Important advances in cosmological studies with SNe and strongly lensed systems in the new era of large-area, high-cadence optical surveys such as LSST will require single-object follow-up data of several types:

- Spectrophotometry of SNe Ia will enable direct cosmological measurements, the calibration of photometric classification performance at high redshift (where it is the most uncertain), and tests of systematic effects. Given the wide range of LSST SN brightnesses, this work will be reliant on large amounts of low-to-medium resolution spectroscopy on ground-based telescopes with apertures from 4 m to > 20 m, and, ideally, space-based telescopes as well.
- Follow-up imaging with more frequent cadence than LSST will be valuable for measuring strong lensing time delays; this can generally be conducted on 2–4 m telescopes.
- Adaptive optics IFU spectroscopy, or AO imaging plus slit spectroscopy, is needed for precision image position measurements and lens system modeling; this work will require access to both 8–10 m and > 30 m telescopes with AO capabilities.

The Kavli/NOAO/LSST report provided quantitative estimates of the telescope time required to support cosmology measurements with LSST supernovae and strong-lens systems[21] (see[1] for a summary). Although in many cases suitable instruments exist (e.g., Keck/OSIRIS) or are being developed (e.g., Gemini/SCORPIO), cases remain where the telescopes best positioned for this work have suboptimal instrumentation; as a result, additional instrument development, not just telescope time, may be needed to fully take advantage of the potential to study cosmology with LSST supernovas and strong lens systems.

Authors: R. Hložek (U. Toronto, Dunlap Institute for Astronomy and Astrophysics), D. J. Perrefort (U. Pittsburgh, PITT PACC), T. Collett (IoCG, Portsmouth), L. Galbany (U. Pittsburgh, PITT PACC), D. A. Goldstein (Caltech, Hubble Fellow), M. Ishak (UT Dallas), S. W. Jha (Rutgers), A. G. Kim (LBNL), R. Mandelbaum (CMU), J. A. Newman (U. Pittsburgh, PITT PACC), S. Perlmutter (LBNL, UC Berkeley), M. Sullivan (Southampton), and A. Verma (U. Oxford), for the LSST Dark Energy Science Collaboration

Acknowledgements

The LSST Dark Energy Science Collaboration acknowledges ongoing support from the Institut National de Physique Nucléaire et de Physique des Particules in France; the Science & Technology Facilities Council in the United Kingdom; and the Department of Energy, the National Science Foundation, and the LSST Corporation in the United States. DESC uses resources of the IN2P3 Computing Center (CC-IN2P3–Lyon/Villeurbanne - France) funded by the Centre National de la Recherche Scientifique; the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231; STFC DiRAC HPC Facilities, funded by UK BIS National E-infrastructure capital grants; and the UK particle physics grid, supported by the GridPP Collaboration. This work was performed in part under DOE Contract DE-AC02-76SF00515.

References

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

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

[3] T. de Jaeger, L. Galbany, A. V. Filippenko, et al. SN 2016jhj at redshift 0.34: extending the Type II supernova Hubble diagram using the standard candle method. *MNRAS*, 472:4233–4243, Dec 2017.

[4] C. Inserra, R. C. Nichol, D. Scovacricchi, et al. Euclid: Superluminous supernovae in the Deep Survey. *A&A*, 609:A83, Jan 2018.

[5] H. K. Fakhouri, K. Boone, G. Aldering, et al. Improving Cosmological Distance Measurements Using Twin Type Ia Supernovae. *ApJ*, 815:58, Dec 2015.

[6] S. Refsdal. The gravitational lens effect. *MNRAS*, 128:295, 1964.

[7] R. D. Blandford and R. Narayan. Cosmological applications of gravitational lensing. *ARA&A*, 30:311–358, 1992.

[8] D. A. Goldstein, P. E. Nugent, D. N. Kasen, and T. E. Collett. Precise Time Delays from Chromatically Microlensed Type Ia Supernovae. *ArXiv e-prints*, page arXiv:1708.00003, July 2017.

[9] A. G. Riess, L. M. Macri, S. L. Hoffmann, et al. A 2.4% Determination of the Local Value of the Hubble Constant. *ApJ*, 826:56, July 2016.

[10] Planck Collaboration, N. Aghanim, M. Ashdown, et al. Planck intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth. *A&A*, 596:A107, December 2016.

[11] E. Di Valentino, A. Melchiorri, and J. Silk. Reconciling Planck with the local value of H_0 in extended parameter space. *Physics Letters B*, 761:242–246, October 2016.

[12] W. L. Freedman. Cosmology at a crossroads. *Nature Astronomy*, 1:0121, May 2017.

[13] G.-B. Zhao, M. Raveri, L. Pogosian, et al. Dynamical dark energy in light of the latest observations. *Nature Astronomy*, 1:627–632, September 2017.

[14] G. Efstathiou. H_0 revisited. *MNRAS*, 440:1138–1152, May 2014.

[15] J. L. Bernal, L. Verde, and A. G. Riess. The trouble with H_0. *JCAP*, 10:019, October 2016.

[16] É. Aubourg, S. Bailey, J. E. Bautista, et al. Cosmological implications of baryon acoustic oscillation measurements. *Phys. Rev. D*, 92(12):123516, December 2015.

[17] Planck Collaboration, P. A. R. Ade, N. Aghanim, et al. Planck 2015 results. XIII. Cosmological parameters. *A&A*, 594:A13, September 2016.

[18] V. Bonvin, F. Courbin, S. H. Suyu, et al. H0LiCOW - V. New COSMOGRAIL time delays of HE 0435-1223: H_0 to 3.8 per cent precision from strong lensing in a flat ΛCDM model. *MNRAS*, 465:4914–4930, March 2017.

[19] E. V. Linder. Strong gravitational lensing and dark energy complementarity. *Phys. Rev. D*, 70(4):043534, August 2004.

[20] E. V. Linder. Lensing time delays and cosmological complementarity. *Phys. Rev. D*, 84(12):123529, December 2011.

[21] 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.