Snowmass2021 - Letter of Interest

Understanding the accelerated expansion of the Universe with Rubin Observatory's Legacy Survey of Space and Time

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

■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities

Contact Information:
Submitter Name/Institution: Rachel Mandelbaum (Carnegie Mellon University)
Collaboration (optional): LSST Dark Energy Science Collaboration
Contact Email: rmandelb@andrew.cmu.edu

Authors: Camille Avestruz (University of Michigan), Amanda E. Bauer (Vera C. Rubin Observatory/NOIRLab), Simon Birrer (Stanford University), Jonathan Blazek (Northeastern University), Robert Blum (Vera C. Rubin Observatory/NOIRLab), Pat Burchat (Stanford University), Chihway Chang (University of Chicago), Douglas Clowe (Ohio University), Andrew Connolly (University of Washington), Eric Gawiser (Rutgers), Leanne P. Guy (Vera C. Rubin Observatory/NOIRLab), Katrin Heitmann (Argonne National Laboratory), Mustapha Ishak (University of Texas at Dallas), Željko Ivezić (University of Washington), Stephen M. Kahn (Vera C. Rubin Observatory/SLAC), David Kirkby (UC Irvine), Jia Liu (UC Berkeley), Rachel Mandelbaum (Carnegie Mellon University), Yao-Yuan Mao (Rutgers), Phil Marshall (Vera C. Rubin Observatory/SLAC National Accelerator Laboratory), Rogerio Rosenfeld (Instituto de Física Teórica - UNESP & LIneA), Anže Slosar (Brookhaven National Laboratory), Chris Walter (Duke University)

Abstract:[*] Despite two decades of tremendous experimental and theoretical progress, the riddle of the accelerated expansion of the Universe remains to be solved. On the experimental side, our understanding of the possibilities and limitations of the major dark energy probes has evolved greatly in the past decade. On the theoretical side, the taxonomy of explanations for the accelerated expansion rate is better understood, providing clear guidance to the relevant observables. Within this landscape, Rubin Observatory's Legacy Survey of Space and Time (LSST) will enable great advances in our understanding of the accelerated expansion rate of the Universe via a suite of complementary dark energy probes measuring both the expansion history and rate of structure growth. Preparations are well underway within Rubin Observatory and the LSST Dark Energy Science Collaboration (DESC), which must coordinate effectively as they support distinct aspects of HEP's scientific goals for LSST. In this LOI we outline key challenges and opportunities for LSST as a dark energy experiment within the broader HEP landscape of the 2020s. Understanding dark energy, which is arguably the biggest unsolved mystery in fundamental physics, will remain one of the focal points of cosmology in the coming decade.

[*]This LSST-focused LOI is based on a more general submission to the Astro2020 Decadal Survey[1] led by a subset of the authors.

Background: Twenty years since the discovery of cosmic acceleration, the laws of physics on the largest scales remain an enigma. The phenomenon continues to drive us to consider bold transformations in our understanding of cosmic forces. Broadly speaking, theories of dark energy fall into four major classes[1]: the cosmological constant; quintessence-type theories where dark energy is a component with novel properties, typically explained in terms of a scalar field; modified-gravity theories in which cosmic acceleration is caused by some extension of the gravitational sector; and more exotic theoretical paths towards generating accelerated expansion. In all cases, there exist challenges in defining a satisfactory theory that fits all available observations and does not require some new physics[2–6]. The main observables that will help us distinguish between these scenarios are the precise characterization of the *expansion history*, the *gravitational slip* ($\eta = \Phi/\Psi$, where Φ and Ψ are gravitational potentials in the time and space perturbations of the metric) and the *effective large-scale Newton's constant* $G_{\rm eff}$[7]. Both η and $G_{\rm eff}$ are unity in the standard GR, but can be time- and scale-dependent quantities in modified-gravity theories, which has generated interest in measuring the growth of structure and the combination of datasets to constrain these two parameters[8–16].

Faced with this compelling mystery, cosmologists have mounted a multi-faceted campaign to study the behavior of the Universe on large scales. This program has been undeniably successful: data quality has improved radically over the past decade, with new leaps expected early in the 2020s from upcoming facilities. In this context, Vera C. Rubin Observatory will carry out the Legacy Survey of Space and Time (LSST[17]) during its first ten years of operation, using the 3.2 Gigapixel Rubin Observatory LSST Camera and the 8.4-m Simonyi Survey Telescope. The LSST Dark Energy Science Collaboration (DESC) is the international science collaboration that will make high-accuracy measurements of fundamental cosmological parameters using data from the LSST. With cosmology (broadly) as one of its science pillars, the LSST promises to greatly increase the discovery space across many areas of astronomy. Its promise for constraining the dark energy equation of state has been quantified by the LSST DESC[18]; by combining multiple probes of structure growth and the expansion history, LSST will be a Stage IV dark energy experiment as defined by the Dark Energy Task Force[19].

Entering the decade of precision dark energy science with LSST: A rich portfolio of observational methods will drive the study of cosmic acceleration in the coming decade across all experiments, and even with LSST data alone. The methods reinforce each other both in terms of statistical leverage and control of systematic uncertainties. Marginalizing over systematic uncertainties has resulted in expanded parameter spaces, and the field continues to work on building and validating models for major systematic uncertainties that work at the level needed for upcoming surveys.

There are two main classes of methods to study dark energy. The first measures the *expansion history*, particularly through the study of the distance-redshift relation. The second measures the *growth* of matter density fluctuations, which is impacted by large-scale gravitational forces. Dark energy slows the growth of fluctuations and decreases the number of dark matter halos of a given mass. Growth measurements offer more than an increase in statistical precision; they provide an essential consistency check that has the potential to reveal non-standard physics in the gravitational sector. We now briefly summarize the major methods planned for constraining dark energy with LSST.

Type Ia supernovae (SNe Ia) are bright standard candles that probe the expansion history of the Universe by calibrating the luminosity distance as a function of redshift. The combination of ancillary low-redshift data, intermediate-redshift supernovae in the LSST Wide-Fast-Deep survey, and higher redshift supernovae in the LSST Deep Drilling Fields will provide a long redshift baseline. Time delays between multiple **strongly lensed images** of the same object, and static compound lenses, provide measurements of the Hubble parameter independently of other distance measures. This method is powerful with a relatively small sample of lens systems and high-quality follow-up data. The **clustering of galaxies** can be used to reconstruct some of the features left by the cosmic evolution in the distribution of structures through gravitational collapse. This method requires modeling the so-called galaxy bias that relates matter and galaxy fluctuations. Measurements of coherent distortions in galaxy shapes due to **weak gravitational lensing** reveal the distribution of dark matter in the Universe. Combining tomographic auto- and cross-correlations of weak lensing and galaxy positions with measurements of the expansion history may be the most effective way to distinguish between dark energy and modified gravity. **Galaxy clusters** are the most massive, gravitationally bound structures in the Universe; their abundance provides a sensitive probe of growth. The challenge of calibrating mass estimates will be tackled using LSST weak lensing measurements and ancillary data (e.g., X-ray data, and the Sunyaev-Zeldovich effect measured from the CMB).

Conclusions and Outlook: The coming decade will be an exciting one for understanding the accelerated expansion rate of the Universe with the LSST. The combination of high-precision data with growth in theoretical models and statistical techniques will allow a great leap in our cosmological leverage, testing our theories in unprecedented ways and perhaps sharpening the fault lines in present results. Below are some important themes as we look toward the coming decade:

- *Improving statistical and systematic precision on the equation of state is essential,* necessitating thorough efforts to control key limiting systematic uncertainties for the aforementioned probes.
- *Multiple methods bring robustness.* Characterizing dark energy and modified gravity through as many different methods as possible provides valuable consistency tests as methods hit systematic floors.
- *Cross-correlations are ever more important.* Applying similar methods over the same volume brings about numerous cross-correlations that have proven highly valuable. Making maximal use of them requires compatible simulation and data processing/analysis tools across surveys and collaborations.
- *Blind analysis is desirable but challenging, requiring careful methodological planning.* This is especially true with upcoming complex analyses that involve numerous, often subjective, analysis choices.
- *Ancillary data and complementary surveys have the potential to greatly increase the discovery power of LSST.* These enhancements, and the associated analysis tools and coordination, have been considered in detail[20–24] and in many cases, the whole is far more than the sum of the parts.
- *The LSST data will drive evolution in our understanding of analysis methods.* Precursor imaging surveys have brought about substantial updates in our understanding of how to constrain cosmic acceleration in the past 5 years. The increase in data volume and complexity of LSST will revolutionize our understanding and drive development of new, not-yet-envisioned methodology. Robust research support for the duration of the survey will be essential to enable full exploitation of this dataset.
- *Studies of dark energy and modified gravity are related.* They should be studied as one field to understand cosmic acceleration.
- *Rubin Observatory and the LSST DESC work on distinct yet closely-related aspects of HEP's scientific goals for LSST*, and must coordinate effectively to achieve those goals.
- *LSST will drive discovery in fundamental physics well beyond cosmic acceleration.* As we strive to develop robust analysis methodology to constrain cosmic acceleration, we should be mindful of the opportunities to extend those techniques and expand discovery space from this remarkable dataset.

The field of cosmology has been adept at unifying large teams to produce and optimize state-of-the-art facilities, the products of which have advanced many areas of astrophysics. We believe that the mystery of dark energy and the diverse range of measurements that bear on it remains a compelling driver to motivate this development in the coming decade.

References

[1] A. Slosar et al., *Dark Energy and Modified Gravity*, BAAS **51** (2019) 97 [1903.12016].

[2] A. Padilla, *Lectures on the Cosmological Constant Problem*, 1502.05296.

[3] C.P. Burgess, *The Cosmological Constant Problem: Why it's hard to get Dark Energy from Micro-physics*, in *Proceedings, 100th Les Houches Summer School: Post-Planck Cosmology: Les Houches, France, July 8 - August 2, 2013*, pp. 149–197, 2015, DOI [1309.4133].

[4] P. Agrawal, G. Obied, P.J. Steinhardt and C. Vafa, *On the Cosmological Implications of the String Swampland*, *Phys. Lett.* **B784** (2018) 271 [1806.09718].

[5] L. Heisenberg, M. Bartelmann, R. Brandenberger and A. Refregier, *Dark Energy in the Swampland*, *Phys. Rev.* **D98** (2018) 123502 [1808.02877].

[6] C. de Rham and S. Melville, *Gravitational Rainbows: LIGO and Dark Energy at its Cutoff*, *Phys. Rev. Lett.* **121** (2018) 221101 [1806.09417].

[7] I.D. Saltas, L. Amendola, M. Kunz and I. Sawicki, *Modified gravity, gravitational waves and the large-scale structure of the Universe: A brief report*, *arXiv e-prints* (2018) arXiv:1812.03969 [1812.03969].

[8] R. Reyes, R. Mandelbaum, U. Seljak, T. Baldauf, J.E. Gunn, L. Lombriser et al., *Confirmation of general relativity on large scales from weak lensing and galaxy velocities*, Nature **464** (2010) 256 [1003.2185].

[9] T. Clifton, P.G. Ferreira, A. Padilla and C. Skordis, *Modified gravity and cosmology*, Phys. Rep. **513** (2012) 1 [1106.2476].

[10] L. Amendola, M. Kunz, M. Motta, I.D. Saltas and I. Sawicki, *Observables and unobservables in dark energy cosmologies*, Phys. Rev. D **87** (2013) 023501 [1210.0439].

[11] D. Huterer et al., *Growth of Cosmic Structure: Probing Dark Energy Beyond Expansion*, *Astropart. Phys.* **63** (2015) 23 [1309.5385].

[12] D. Alonso, E. Bellini, P.G. Ferreira and M. Zumalacárregui, *Observational future of cosmological scalar-tensor theories*, *Phys. Rev.* **D95** (2017) 063502 [1610.09290].

[13] A. Spurio Mancini, R. Reischke, V. Pettorino, B.M. Schäfer and M. Zumalacárregui, *Testing (modified) gravity with 3D and tomographic cosmic shear*, MNRAS **480** (2018) 3725 [1801.04251].

[14] R. Reischke, A.S. Mancini, B.M. Schäfer and P.M. Merkel, *Investigating scalar-tensor gravity with statistics of the cosmic large-scale structure*, MNRAS **482** (2019) 3274 [1804.02441].

[15] A. Spurio Mancini, F. Köhlinger, B. Joachimi, V. Pettorino, B.M. Schäfer, R. Reischke et al., *KiDS+GAMA: Constraints on Horndeski gravity from combined large-scale structure probes*, *arXiv e-prints* (2019) arXiv:1901.03686 [1901.03686].

[16] M. Ishak, *Testing general relativity in cosmology*, *Living Reviews in Relativity* **22** (2019) 1 [1806.10122].

[17] Ž. Ivezić, S.M. Kahn, J.A. Tyson, B. Abel, E. Acosta, R. Allsman et al., *LSST: From Science Drivers to Reference Design and Anticipated Data Products*, ApJ **873** (2019) 111 [0805.2366].

[18] The LSST Dark Energy Science Collaboration, R. Mandelbaum, T. Eifler, R. Hložek, T. Collett, E. Gawiser et al., *The LSST Dark Energy Science Collaboration (DESC) Science Requirements Document*, *arXiv e-prints* (2018) arXiv:1809.01669 [1809.01669].

[19] A. Albrecht, G. Bernstein, R. Cahn, W.L. Freedman, J. Hewitt, W. Hu et al., *Report of the Dark Energy Task Force*, *arXiv e-prints* (2006) astro [astro-ph/0609591].

[20] B. Jain, D. Spergel, R. Bean, A. Connolly, I. Dell'antonio, J. Frieman et al., *The Whole is Greater than the Sum of the Parts: Optimizing the Joint Science Return from LSST, Euclid and WFIRST*, *arXiv e-prints* (2015) arXiv:1501.07897 [1501.07897].

[21] J. Rhodes, R.C. Nichol, É. Aubourg, R. Bean, D. Boutigny, M.N. Bremer et al., *Scientific Synergy between LSST and Euclid*, ApJS **233** (2017) 21 [1710.08489].

[22] R. Mandelbaum, J. Blazek, N.E. Chisari, T. Collett, L. Galbany, E. Gawiser et al., *Wide-field Multi-object Spectroscopy to Enhance Dark Energy Science from LSST*, BAAS **51** (2019) 363 [1903.09323].

[23] J. Newman, J. Blazek, N.E. Chisari, D. Clowe, I. Dell'Antonio, E. Gawiser et al., *Deep Multi-object Spectroscopy to Enhance Dark Energy Science from LSST*, BAAS **51** (2019) 358 [1903.09325].

[24] J. Rhodes, D. Alonso, B. Ansarinejad, R. Armstrong, J. Asorey, A. Avelino et al., *Cosmological Synergies Enabled by Joint Analysis of Multi-probe data from WFIRST, Euclid, and LSST*, BAAS **51** (2019) 201.