Snowmass2021 - Letter of Interest

The Vera C. Rubin Observatory as a Discovery Facility for Fundamental Physics

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:

The Vera C. Rubin Observatory is currently under construction and will undertake the Legacy Survey of Space and Time (LSST), with goals spanning many topics in physics and astronomy. The Rubin Observatory LSST Dark Energy Science Collaboration (DESC) is a particle physics-style international science collaboration with support from the DOE and foreign partners dedicated to understanding dark energy. There are over 200 "full members" working in the DESC, with nearly 1000 scientists involved. The unprecedented 3.25 gigapixel digital camera at the heart of the telescope is now under construction at SLAC.

The DESC has a focused flagship program to determine the nature of dark energy with the LSST. At the same time, like accelerators and large detectors, the Rubin Observatory should be thought of as a general-purpose discovery facility for fundamental physics. Undertaking a wide range of analyses connected to the core dark energy probes will result in constraints on the properties of dark matter, neutrinos and other fundamental particles and fields. A broad approach will maximize the physics output of the facility, training and analysis opportunities for young scientists, and the chance for unexpected discoveries.

1 Introduction

The DESC was founded to use the Rubin Observatory data to elucidate the nature of dark energy by combining multiple types of LSST measurements. This combined analysis will allow consistency checks and evaluation of systematic uncertainties among the different probes of dark energy. These probes range from measuring the distances and redshifts of exploding supernovae, to determining the growth of the largest structures in our universe. **Careful studies of the probes needed for dark energy also allow for exploration of other deep fundamental physics questions being explored by the HEP community.**

2 The Rubin Observatory as a Discovery Facility for Fundamental Physics

Whenever a new class of accelerator or experiment comes on line, especially those offering completely new kinds of data to explore or massive increases in statistics, opportunities for discovery have followed. From when Rabi exclaimed "Who ordered that?" when muons were found in cosmic rays, to the confirmation of tetra-quarks by LHCb at the LHC, paths to discovery are often not linear. We must extract as much physics from each of these facilities as we can and should always be on the lookout for surprises.

The Rubin Observatory and the DESC are exactly this sort of facility and experiment. Rubin Observatory's LSST will catalog approximately 37 billion objects, more than all previous astronomical surveys combined; these data will allow us to investigate the universe with an unprecedented level of detail. The Rubin Observatory will do this work contemporaneously with the next generation of Cosmic Frontier experiments such as DESI and CMB-S4. Each brings its own strengths. Eventually, joint considerations of their data sets will maximize their scientific impact.

The measurement of dark energy is the primary science driver for the DESC and sets the technical requirements we must meet. To undertake this mission, the DESC needs to study multiple data sets that probe dark energy. Many of these probes are naturally connected to other fundamental physics questions and properties. We list a subset here:

1. **Dark Matter**: We cannot actually "see" dark energy; it appears to be a property of space-time itself. We infer the properties of dark energy by measuring its effects on both the normal matter and dark matter in our universe. Thus, to study dark energy, we must measure dark matter. The DESC **will** "see" the dark matter, both directly via gravitational lensing, and indirectly by using normal matter to trace its structure. These measurements are an opportunity to understand the fundamental nature of dark matter. Currently, astrophysical studies provide the only robust empirical measurements of dark matter.[1–3] DESC studies of dark matter go hand-in-hand with dark matter direct detection experiments and indirect searches for dark matter annihilation/decay into standard model particles.[4] A complete picture of dark matter properties can only be formed by combining all of these experimental measurements and checking their consistency.[5]
2. **Neutrino Mass**: The energy density of neutrinos in the universe is comparable to that of photons. Their mass plays a role in how the universe evolves, and the fact that they are so light yet not massless, gives neutrinos a unique role in cosmology. In the hot, early universe, they act as massless particles, like photons. But then, as the universe cools, they become non-relativistic, acting like dark matter. In this form, they alter how giant structures in the universe develop, changing the relative clumpiness between the largest and smallest scales. These effects allow us to infer neutrino properties, including the sum of masses of all the neutrino types, and possibly will exclude one of the mass orderings.[6] If the absolute neutrino mass is small and the ordering is normal, astrophysical surveys may be the only way we will be able to determine the ordering. The Rubin Observatory and the DESI and CMB-S4

projects can all make unique contributions to our understanding of neutrinos, and will be especially powerful when combined.[7–11]

3. **The Nature of Gravity**: General Relativity (GR) describes the behavior of matter on both the largest and smallest scales. Modifications to the current picture including quantum fields that couple to gravity provide an alternative explanation for the accelerating expansion of the universe without invoking dark energy.[12–14] The DESC can distinguish this explanation from others by comparing the gravitational growth of the largest structures in our universe with the overall expansion history of the universe.[15,16]

4. **Inflationary Physics**: Much can be learned about the high-energy physics in the early Universe by studying the statistical properties of the initial density fluctuations. The theory of inflation predicts that their distribution should be almost Gaussian. Constraining the level of non-Gaussianity would provide invaluable information with which to discriminate between different inflationary models.[17] This primordial non-Gaussianity leaves a distinct imprint in the distribution of galaxies in the form of extra power on very large scales,[18] and could also impact galaxy shape correlations.[19] In order to detect this signal, surveys must cover large volumes with a high number density of sources that can be separated into distinct tracers of the matter density,[20] all strengths of the Rubin Observatory. Forecasts show that the LSST should yield constraints comparable to, or better than, any other facility of its generation.[21] These constraints could be significantly improved by combining with observations of CMB secondary anisotropies.[22]

All large international collaborations have flagship analyses, but they are coupled with exploratory analyses to find the unexpected and extract the most physics for the investments that have been made. For example, while we search for and study the Higgs, we also look for direct dark matter production, SUSY, and technicolor. In the intensity frontier, Super-Kamiokande, Minos and T2K have searched for violations of Lorentz Invariance. This will continue in DUNE, with searches for proton decay to probe the GUT scale and neutrinos from supernovae to learn their properties. The Rubin Observatory and DESC should be no different. Exploring the topics above will extract the maximum physics from the facility and bring with it a host of other benefits. The advantages of performing a varied and wide set of analyses include the following:

- Maximizes the physics output of the facility.
- Provides thesis projects for the large number of students who have built the tools and hardware.
- Trains the technical work force in the wide variety of tools they need to bring to industry and our national laboratories. E.g., DESC has a large effort centered around machine learning and many students are interested in bringing their gained expertise to the non-academic sphere.
- Leads to unexpected discoveries! For example, atmospheric neutrino oscillations were first noticed by researchers trying to understand the backgrounds for proton decay. The wider the physics program, the better the chance of noticing something important and unexpected. The data set from the Rubin Observatory will be ground-breaking in its size and sensitivity. We must make the most of it and be prepared for the unexpected!

All of the topics mentioned here are already within the portfolio of research funded by the DOE Office of Science. Some, like neutrino properties, are also science drivers of other DOE-funded CF experiments like CMB-S4 and DESI. To maximize the substantial investment in the Rubin Observatory, DESC should be considered a multi-faceted experiment with a flagship dark energy program. Along with that understanding should come research support for other fundamental physics topics that are at the core of our mission as physicists.

References

[1] G. Bertone and D. Hooper, *History of dark matter*, *Rev. Mod. Phys.* **90** (2018) 045002 [`1605.04909`].

[2] M. R. Buckley and A. H. G. Peter, *Gravitational probes of dark matter physics*, *Phys. Rept.* **761** (2018) 1 [`1712.06615`].

[3] P. D. Group, P. A. Zyla, R. M. Barnett, J. Beringer, O. Dahl, D. A. Dwyer et al., *Review of Particle Physics, Chapter 27*, *Progress of Theoretical and Experimental Physics* **2020** (2020) .

[4] A. Drlica-Wagner et al., *Probing the Fundamental Nature of Dark Matter with the Large Synoptic Survey Telescope*, `1902.01055`.

[5] SNOWMASS 2013 COSMIC FRONTIER WORKING GROUPS 1–4 collaboration, *Dark Matter in the Coming Decade: Complementary Paths to Discovery and Beyond*, *Phys. Dark Univ.* **7-8** (2015) 16 [`1305.1605`].

[6] J. Lesgourgues and S. Pastor, *Massive neutrinos and cosmology*, *Phys. Rept.* **429** (2006) 307 [`astro-ph/0603494`].

[7] A. Font-Ribera, P. McDonald, N. Mostek, B. A. Reid, H.-J. Seo and A. Slosar, *DESI and other dark energy experiments in the era of neutrino mass measurements*, *JCAP* **05** (2014) 023 [`1308.4164`].

[8] S. Mishra-Sharma, D. Alonso and J. Dunkley, *Neutrino masses and beyond- ΛCDM cosmology with LSST and future CMB experiments*, *Phys. Rev. D* **97** (2018) 123544 [`1803.07561`].

[9] B. Yu, R. Z. Knight, B. D. Sherwin, S. Ferraro, L. Knox and M. Schmittfull, *Towards Neutrino Mass from Cosmology without Optical Depth Information*, `1809.02120`.

[10] M. Gerbino and M. Lattanzi, *Status of neutrino properties and future prospects for cosmological and astrophysical constraints*, *Frontiers in Physics* **5** (2018) 70.

[11] C. Mahony, B. Leistedt, H. V. Peiris, J. Braden, B. Joachimi, A. Korn et al., *Target neutrino mass precision for determining the neutrino hierarchy*, *Phys. Rev. D* **101** (2020) 083513 [`1907.04331`].

[12] G. W. Horndeski, *Second-Order Scalar-Tensor Field Equations in a Four-Dimensional Space*, *International Journal of Theoretical Physics* **10** (1974) 363.

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

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

[15] M. Ishak, T. Baker, P. Bull, E. M. Pedersen, J. Blazek, P. G. Ferreira et al., *Modified Gravity and Dark Energy models Beyond $w(z)$CDM Testable by LSST*, *arXiv e-prints* (2019) arXiv:1905.09687 [`1905.09687`].

[16] T. Baker, A. Barreira, H. Desmond, P. Ferreira, B. Jain, K. Koyama et al., *The Novel Probes Project – Tests of Gravity on Astrophysical Scales*, *arXiv e-prints* (2019) arXiv:1908.03430 [`1908.03430`].

[17] N. Bartolo, E. Komatsu, S. Matarrese and A. Riotto, *Non-Gaussianity from inflation: Theory and observations*, *Phys. Rept.* **402** (2004) 103 [`astro-ph/0406398`].

[18] N. Dalal, O. Dore, D. Huterer and A. Shirokov, *The imprints of primordial non-gaussianities on large-scale structure: scale dependent bias and abundance of virialized objects*, *Phys. Rev. D* **77** (2008) 123514 [`0710.4560`].

[19] F. Schmidt, N. E. Chisari and C. Dvorkin, *Imprint of inflation on galaxy shape correlations*, *JCAP* **2015** (2015) 032 [`1506.02671`].

[20] U. Seljak, *Extracting primordial non-gaussianity without cosmic variance*, *Phys. Rev. Lett.* **102** (2009) 021302 [`0807.1770`].

[21] D. Alonso and P. G. Ferreira, *Constraining ultralarge-scale cosmology with multiple tracers in optical and radio surveys*, *Phys. Rev. D* **92** (2015) 063525 [`1507.03550`].

[22] M. Schmittfull and U. Seljak, *Parameter constraints from cross-correlation of CMB lensing with galaxy clustering*, *Phys. Rev. D* **97** (2018) 123540 [`1710.09465`].

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