Snowmass2021 - Letter of Interest

Theory and Computing Across LSST, DESI, and CMB-S4

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) *CompF2: Theoretical Calculations and Simulation*

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Abstract: With the Legacy Survey of Space and Time (LSST), Dark Energy Spectroscopic Instrument (DESI), and CMB-S4, we are entering an exciting phase during which we expect more than an order of magnitude improvement in the combined constraints on dark energy, neutrinos, and inflation. Although not a traditional construction project, a "Small Project" effort to establish common infrastructure in theory and simulations across these three programs will greatly enhance the science reach beyond what is possible with any single experiment. We present a coordinated program of simulations and theoretical modeling to enable new insights into fundamental physics through small-scale clustering and cross-correlation studies from LSST, DESI, and CMB-S4.

Following the advocacy from previous white papers[1], theory and simulation development will allow us to extract cosmological information from small scales and optimize cross-correlation studies. Here, we describe those two areas of theory and simulations that could advance studies of the cosmological model if pursued in a coordinated fashion across the LSST, DESI, and CMB-S4 flagship surveys. The combination of these approaches will help establish if cosmic acceleration is due to a cosmological constant (Λ), dark energy, or a modification to GR; determine the sum of neutrino masses; and elucidate the mechanism behind inflation.

By investing in new directions in simulation-based theoretical modeling, we can lay the foundation for a new generation of cosmological inference that unlocks the predictive power of the world's largest cosmological simulations. A program in theory and simulations can dramatically enhance the scientific returns of upcoming surveys, and advance the field of computational cosmology into the era of exascale computing. A close coupling of simulations, modeling, and data analysis spanning the cosmic, theory, and computational frontiers in DOE is necessary – this LOI describes the areas that require significant new effort.

1 The nonlinear regime of matter and galaxy clustering

Improved modeling of survey observables on moderately nonlinear scales will pay direct dividends in providing stronger cosmological constraints from LSST, DESI and CMB-S4. Measurements of nonlinear scales substantially increases the number of independent modes of the density field that can be used to probe the physics of dark energy. Moreover, the nonlinear regime could contain distinctive signatures of deviations from GR, such as environment-dependent gravitational screening.

To access the cosmological constraining power of small-scale information, robust theoretical modeling of the nonlinear regime is required. It has been suggested for some time that if the effects of gravitational collapse and baryonic matter can be encapsulated by a combination of empirical and theoretical modeling, then extending probes of large-scale structure well into the nonlinear regime can significantly improve dark energy constraints, even when self-calibrating a reasonably large number of "nuisance parameters".

The LSST-DESC Science Requirement Document relies on galaxy correlations limited to $k_{\max} = 0.3\,h$/Mpc, while the DESI projections assume $k_{\max} = 0.2\,h$/Mpc in RSD studies. Meanwhile, CMB-S4 will detect galaxy clusters past $z = 2$ through the thermal Sunyaev-Zel'dovich (SZ) effect. Extracting information from smaller scales will only be possible if reliable predictions are available. This will require a rigorous simulation and modeling effort of baryons, dark matter, and the connection between galaxies, clusters, and halos. Applications of the galaxy halo occupation and effective field theory frameworks are required to model the LSST and DESI data, while additional models may be required to draw inference from the CMB-S4 cluster data. Numerical simulations that can jointly inform lensing, redshift, and SZ surveys are required to test the reliability of those theoretical models.

A community effort is needed to develop the range of software, theory, and simulation data products needed for these measurements at small scales. Software is required for modeling of small-scale two-point correlations of dark matter and baryons, calibrating the masses of high-redshift clusters through gravitational lensing, and incorporating estimates of theoretical uncertainties. In particular these predictions will be enabled by building emulators. The theory must account for astrophysical systematic errors that critically impact cosmology and are addressed by both effective field theory approaches and advanced modeling of the galaxy-halo connection. Parallel studies on shared catalogs (both simulated and real) are required to assess consistency between theoretical approaches. The software must also incorporate the models and systematic errors in the analysis of cosmological parameters. Finally, the simulation data products must include mock catalogs of galaxies, clusters, lensing, and other observables. These simulations would include a variety of scenarios based on both gravity-only and hydrodynamical simulations.

2 Multi-wavelength cosmology

Shared simulations with proper systematic errors and covariances will facilitate cross-correlation studies between the three flagship surveys. At high redshift, LSST galaxies, CMB-S4 lensing, and DESI spectroscopy can be jointly used to constrain primordial non-Gaussianities, growth of structure, and the neutrino mass. Joint studies of redshift space distortions (RSD), thermal and kinetic SZ effect in clusters, and LSST lensing can be used at lower redshift to further constrain the nature of dark energy and test physics beyond the standard model, such as modifications to General Relativity. Measurements in each of these regimes can potentially yield constraining power that vastly exceeds the standard projections for constraints on dark energy, inflation, and neutrino masses.

Control of systematic errors will be critical to fully extract the cosmological information from cross-correlation studies, as will the development of new methodologies to combine multi-wavelength data sets from different cosmological probes. For example, the inclusion of CMB lensing from CMB-S4 into an LSST galaxy clustering and weak lensing analysis can mitigate shear systematic errors at high redshift through self-calibration[2]. Spectroscopic redshifts can be used to calibrate the redshift distributions for studies of primordial non-Gaussianity with CMB lensing and galaxy clustering[3].

A comprehensive effort in analysis, modeling, and simulations for multi-wavelength data would require "same sky mocks" for the different observables and related systematic errors covered by the three surveys. The mocks will need to include proper correlations between all of the signals that will be measured. On the analysis front, software is needed that utilizes nuisance parameters, bias models, covariances, and systematic models jointly between signals. Creating a multi-wavelength virtual observatory across all observables is a challenging task. More limited and approximate products would still enhance the joint analysis of large-scale structure and CMB datasets. Gravity-only simulations, as for the small scales effort, would be the bedrock for the optical sky catalogs, CMB lensing measurements, and also allow the modeling of foregrounds relevant for the CMB surveys, such as the cosmic infrared background. Hydrodynamics simulations with different implementations of feedback will be important for, e.g., cluster cosmology investigations, Lyman-α observables and other physics. In addition to the simulation efforts, building and validating tools to create synthetic skies are essential. Some of these tools already exist but will need to be sharpened. Close collaboration between the surveys would be essential to fully realize the potential of the multi-wavelength mock catalogs.

3 Small Project Effort

A simulation and theory program will address the challenge of extracting cosmological information from small scales and establish the analysis infrastructure that will reach across the DOE flagship surveys in dark energy and inflation. This ambitious program relies on strong university-lab partnerships in computing, expertise in theory, and a deep knowledge of the spectroscopic, imaging, and CMB data samples. To realize the gains in cosmological precision with these enhanced analyses is only possible with a holistic program that incorporates the community's broad expertise in a programmatic fashion. We therefore recommend a coordinated effort in simulation and theory that is analogous to a small construction project to expand the results from of DESI, LSST, and CMB-S4 beyond the baseline projections.

References

[1] Dawson K., Frieman J., Heitmann K., Jain B., Kahn S., Mandelbaum R., Perlmutter S., Slosar A., 2018, arXiv e-prints, p. arXiv:1802.07216

[2] Schaan E., Krause E., Eifler T., Doré O., Miyatake H., Rhodes J., Spergel D. N., 2017, Phys. Rev. D, 95, 123512

[3] Schmittfull M., Seljak U., 2018, Phys. Rev. D, 97, 123540

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