Snowmass2021 Letter of Interest: Improving Cosmological Constraints by Cross-correlating Galaxy and CMB surveys

Thematic Areas:

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

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Abstract:

Perturbations to the observed cosmic microwave background (CMB) caused by late-time large-scale structure result in correlations between galaxy and CMB surveys. Measurement of these correlations enables extraction of information about large-scale structure that is otherwise inaccessible by the individual surveys alone. These measurements are also less prone to many systematic effects because different surveys typically have uncorrelated instrumental noise and sources of systematic bias. This letter of interest focuses on the correlations of four observables: galaxy positions, galaxy lensing shears, CMB lensing, and the thermal Sunyaev-Zel'dovich effect. These observables will be measured at high signal-to-noise by upcoming galaxy and CMB surveys such as the Vera Rubin Observatory LSST, Roman Space Telescope, the Euclid mission, Simons Observatory, and CMB Stage 4. The expected science return from analysis of cross-correlations between these observables is multi-fold — we expect to achieve tighter and more robust constraints on fundamental physics, such as the equation of state of dark energy and primordial non-Gaussianity, and astrophysical effects, such as galaxy biasing, intrinsic alignment, and baryonic feedback. To perform robust cross-correlation analyses with these upcoming large surveys, we need to develop improved theoretical models and correlated simulations. In addition, collaborations also need to coordinate their observational strategies, analysis pipelines, and support infrastructures.

Overview

Although cosmic microwave background (CMB) photons are sourced from $z \sim 1100$, gravitational lensing and the Sunyaev Zel'dovich (SZ) effect mean that observations of the CMB are sensitive to late-time large-scale structure (LSS). Mapping the secondary anisotropies induced by these effects is a key goal of planned high-resolution CMB experiments, like Simons Observatory (1) and CMB Stage 4 (2). However, a fundamental limitation of CMB probes of late-time structure is that observations of the CMB are projected along the line of sight, and therefore cannot directly probe the redshift evolution of structure. In contrast, planned galaxy imaging surveys like the Vera Rubin Observatory's Legacy Survey of Space and Time (LSST; (3)), the Nancy Grace Roman Space Telescope (4), and the Euclid mission (5) will map structure in bins of photometric redshift using the distribution of galaxies and galaxy lensing. A limitation of lensing measurements from these future surveys, though, is that their sensitivity will decline quickly beyond $z \gtrsim 2$ due to a lack of suitable source galaxies at high redshift (6).

By cross-correlating CMB surveys with galaxy imaging surveys, we can exploit the relative advantages of both survey types and maximize their total science return. Here we focus in particular on correlations between four observables that will be measured by these surveys with large signal-to-noise: galaxy positions, galaxy lensing shears, CMB lensing and the thermal SZ effect (tSZ). The cross-correlation of galaxies that are isolated in redshift space (i.e via photometric redshifts) with a projected probe, like CMB lensing or the tSZ effect, can be used to separate the contributions to the projected field from different redshift bins, effectively turning the 2D projected measurements into 3D probes (7; 8). Furthermore, cross-correlations can exploit the complementarity of galaxy and CMB survey measurements. CMB lensing is most sensitive to structure at $z \sim 2$, and continues to be sensitive out to much higher redshift (9). Galaxy lensing measurements from e.g. LSST, on the other hand, will be most sensitive to $z \sim 0.1 - 1.5$ (10). By cross-correlating galaxies with *both* galaxy lensing and CMB lensing, we can exploit the relative strengths of the two lensing measurements (11).

Challenges

Analyses of multiple two-point functions between galaxy and CMB surveys enable several exciting science cases, as we discuss below. However, performing these joint analyses will require significant effort, both from a modeling standpoint and in organizing the different communities and projects for joint analyses.

Correlated simulations and improved modeling: In order for galaxy and CMB surveys to forecast joint constraints and to study relevant systematics, these surveys will need simulations with the same underlying large-scale structure. Currently, however, simulations are usually performed separately within each survey. CMB secondary and foreground simulations (e.g. tSZ, kinematic SZ, cosmic infrared background) typically involve painting the pressure, velocity, or gas density profiles onto simulated dark matter halos (e.g. 12). Galaxy surveys, on the other hand, usually adopt a combination of N-body simulations and halo occupation distribution models to inject galaxies. Compared to CMB simulations, they tend to be more accurate on small scales but often with limited sky coverage due to the high cost of N-body simulations (13–15). For cross-correlation science, additional computing resources are needed to develop fast and accurate simulations to accommodate the scientific requirements for multiple surveys. More, improved theoretical modeling (e.g. 16) is required to optimally extract information from these correlated data sets.

Cross-survey collaboration: The analysis of cross-correlations between galaxy and CMB surveys requires cross-survey collaboration. At the most basic level, surveys must coordinate observation strategies to ensure maximal overlapping sky coverage. Joint analyses of cross correlations also require shared efforts to develop necessary analysis tools and to ensure that all relevant systematic effects are modeled correctly. Finally, surveys must have infrastructure and policies in place for proposing cross-correlation projects, reviewing joint-collaboration publications, and making data products available to the community.

Expected Science Return

Tighter and more robust cosmological constraints: Cross-correlations between galaxy and CMB surveys contain additional information about large-scale structure beyond that contained in intra-survey correlations, and are therefore guaranteed to improve cosmological constraints when jointly analyzed with intra-survey correlations. Cosmological constraints are further improved by the fact that parameter dependencies of cross-correlations are often different from intra-survey correlations, enabling significant degeneracy breaking (17). Cross-survey correlations also tend to be more robust to systematic effects than internal correlations since systematic effects are (in most cases) unlikely to correlate across surveys (17; 18). We describe a few of the interesting applications of galaxy-CMB survey cross-correlations below.

Galaxy biasing and intrinsic alignments: The complex astrophysics that determines where galaxies form ("biasing") and their intrinsic shapes ("intrinsic alignments") can substantially affect the cosmological interpretation of galaxy surveys and the cosmological constraints inferred from them (19–21). Since we must understand how these properties and their evolution depend on the underlying density field, correlating galaxy positions and shapes with CMB lensing, an independent mass tracer, provides a powerful method to improve our understanding of these effects and to mitigate systematic biases (22–24)

Understanding the effects of feedback on the matter power spectrum: The matter power spectrum on small scales ($k \gtrsim 0.1$) is significantly impacted by difficult-to-model and poorly understood baryonic feedback effects. Our inability to model these scales accurately limits our ability to use measurements on these scales to constrain cosmology (25). This is especially unfortunate, since small scales are measured extremely precisely owing to the large number of small-scale modes. The cross-correlation of galaxy surveys with observations of the tSZ effect provides a powerful route to constraining baryonic feedback effects. The tSZ effect is sensitive to the electron gas pressure, and is therefore more sensitive to changes in the thermal energy of the gas than measurements of, for instance, gravitational lensing, which are typically used to constrain cosmology. Consequently, by measuring cross-correlations between galaxy positions and galaxy shears with tSZ maps, we can constrain feedback models (26), ultimately extending the reach of cosmological analyses to smaller scales, and enabling tighter cosmological constraints (27).

Primordial non-Gaussianity: Multi-field inflation models can generate local primordial non-Gaussianity, i.e. initial fluctuations that make small-scale fluctuations depend on the local long-wavelength fluctuation. The tightest limit on this signal comes from CMB observations (28). In the future, large-scale structure observations will play a leading role in the continued search for this signal and tightening the constraints. The constraining power can benefit from observing multiple tracers of large-scale structure that are biased differently with respect to the underlying large-scale structure, reducing the naive limitation from cosmic variance (29; 30). One example of this is the joint analysis of large-scale structure traced by CMB lensing and by galaxy surveys. In that case, the joint analysis can yield two times tighter results, provided the surveys overlap on a large sky area and noise levels are comparable to CMB-S4 CMB lensing and LSST galaxy clustering (31; 32).

Summary

Construction of next generation galaxy and CMB surveys is underway, and even more ambitious surveys are planned for the not too distant future. These surveys will probe the large-scale structure of the Universe with unheralded precision. We have the ability to significantly improve the science return from these large investments by measuring cross-survey correlations. In some sense, cross-correlations come for free: as long as the galaxy and CMB surveys have significant overlap, cross-correlations can be measured. However, we should be prepared to actually analyze these correlations with necessary cross-collaboration infrastructure. Developing such infrastructure will require significant cross-collaboration coordination and investment.

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