Snowmass2021 Letter of Interest:
Multi-Wavelength Simulations

Thematic Areas:

☐ (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
■ (CompF2) Theoretical Calculations and Simulation

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Abstract:

On-going experiments have demonstrated that cross-correlations between probes can be used to unravel astrophysical and cosmological information that is challenging to extract using any single experiment alone. We anticipate that combinations of future experiments such as Euclid, the Vera Rubin Observatory (VRO), Roman Grace Space Telescope, SPHEREx, SKA and CMB-S4, will make measurements of these cross-correlations with signal-to-noise ratio (SNR) exceeding that of current experiments by more than an order of magnitude. Additionally, synergies between different experiments will help us minimize systematic biases present in individual surveys, and is therefore a crucial aspect of future experiments in achieving their scientific goals. While many analytical forecasting frameworks exist in the literature, intricate simulations, which capture much of the relevant physics, and contain correlations between probes, *especially those consisting of observables from different wavelength experiments* are currently limited. In this letter, we will posit that such simulations will be an imperative tool in analyzing cross-correlations between data sets, especially when pushing to smaller (nonlinear) scales.

Overview

In recent years, the role of cosmological simulations has become increasingly important in analyses, especially in modeling the highly nonlinear evolution of the Universe, which is challenging to describe analytically. They have been used to make precise predictions of observables for various cosmologies (1–3), to estimate the covariances of observables (4), and explore cosmological models beyond the standard ΛCDM model (5). As the quality and volume of observational data increase, the requirements on the precision of the model predictions will become more stringent, and therefore, the demand for higher resolution and/or larger volume simulations will continue to grow. Furthermore, future experiments will measure the quasilinear to fully nonlinear scales with high SNR, making these simulations essential for extracting maximal information from these experiments.

While simulations geared towards a particular probe satisfying the requirements of a specific survey has a well-defined road map, simulations capable of describing more than one probe, especially those consisting of *more than one experiment*, are less developed and discussed in the community. Since an immense amount of cosmological and astrophysical information could be extracted from combinations of observables from different surveys, the development of such simulations is of great interest.

List of probes and observables

We list some observables we intend to implement and a short description of how they are related to another.

- **Galaxy clustering/lensing, cluster clustering/lensing/counts**: These are the key observables for photometric galaxy surveys (see 6–8). While the 2-point correlation function has been commonly used to measure these observables (9), there has been an increased interest in applying higher-point correlation functions (10) as well as alternate summary statistics that captures higher-order information (11–13) to extract additional signal from the non-Gaussian density fields. Suites of simulations are needed to make predictions for these summary statistics since analytical frameworks do not exist. Additionally, multi-wavelength simulations of galaxies will allow us to test our detection/deblending pipelines, improve photometric redshift error estimations and validate shape measurements through cross-correlations (14).

- **Spectroscopic galaxies**[1]: Spectroscopic instruments (15–19) measure redshifts, radial velocities, gas dynamics and chemical compositions of galaxies. Cosmological information will be extracted through Baryonic Acoustic Oscillation (BAO) and redshift space distortions (RSD) measurements (20). These galaxies are ideal for galaxy–galaxy lensing analyses (21), as well as for calibrating photometric redshifts using the clustering redshift technique (22; 23). When correlated with CMB temperature maps, the distribution of gas in low mass systems can be mapped out by using the kinetic Sunyaev Zel'dovich (kSZ) effect (24–26). Additionally, Lyman-α forest can be used to measure the three-dimensional power spectrum to intermediate redshifts (27), which can be correlated with galaxy/CMB lensing (28).

- **CMB Lensing**: Lensing of the cosmic microwave background (CMB) measures the integrated mass between the last scattering surface and us. Experiments such as CMB-S4, will produce clean (i.e. polarization based) maps of the integrated mass at high detection significance (29). Since it is sensitive to the full redshift range of the observable Universe, it is correlated with all of the other probes listed (30; 31). It is especially useful for weighing distant objects that are beyond the redshifts ranges accessible through optical weak lensing (32).

- **tSZ/kSZ**: Both the thermal (tSZ) and kinetic Sunyaev Zel'dovich (kSZ) effects are sensitive to the distribution of gas in the Universe. The SZ effects are strongly correlated with the locations of high gas densities such as in galaxy clusters, and are hence correlated with lensing (33) and X-ray (34) observations.

- **CIB**: The cosmic infrared background (CIB) consists of emission from dusty star forming galaxies at $z \sim 2$. The CIB is highly correlated with CMB lensing since their redshift kernels overlaps well, and therefore the CIB has been used to delens the CMB (35; 36). The number counts and clustering measurements of these infrared galaxies as well as their properties such as stellar mass, star formation rate, dust mass, metallicity can give us insights into galaxy evolution (37; 38), and is strongly related to the characterization of galaxies at lower redshifts (39).

- **X-ray maps**: Experiments such as eRosita (40) will measure about $\mathcal{O}(100{,}000)$ clusters of galaxies and 3 million active galactic nuclei over the full sky. By exploiting the tight correlation between X-ray emission and mass, X-ray observations could be used to calibrate mass estimates of SZ-selected clusters (41).

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[1] While there are no differences between photometric and spectroscopic galaxies, we separate these here since their implementation in simulations are significantly different.

- **Line intensity maps**: Experiments such as SPHEREx (42) and SKA (43) will map out the density field at $0.5 \lesssim z \lesssim 3$. While the treatment of foregrounds are anticipated to be challenging, by cross-correlating with CMB lensing maps, density fluctuations of the dark ages could be measured cleanly (44).

Challenges

Volume/Resolution/Number of simulations: A challenging aspect in generating simulations that encompass multiple probes, is the computational cost, as the base simulation needs to meet the requirements of all the individual observables. In addition, some of the observables (such as tSZ/kSZ) would benefit from accompanying hydrodynamical simulations, which are computationally demanding. In estimating covariance matrices where a large number of realizations are essential, approximate methods or machine learning techniques (45) to accelerate the simulation procedure will be required.

Consistent galaxy formation model: Connecting galaxy properties to the underlying dark matter structure in a way that reproduces observed correlations between multi-wavelength observables is a major challenge. Hydrodynamical simulations are capable of making predictions for such correlations, but are too expensive to run in large volumes. As such, development of galaxy formation models that can be applied on dark-matter-only simulations while accounting for the correlations between neutral and ionized gas, stars and dust in galaxies and galaxy clusters will be necessary.

Multi-probe simulations should also offer predictions for the intrinsic shapes of galaxies. The correlations of these shapes, known as their *intrinsic alignments* (IA), is an important systematic effect for next generation weak lensing surveys, but also contain information on galaxy formation and fundamental physics. Currently, galaxy shapes are either drawn from semi-empirical models, which require both high mass resolution simulations and extensive observations (46), or are obtained from hydrodynamical simulations (47; 48) which are computationally infeasible to be run with the required volumes. New techniques to rapidly assign realistic shapes to galaxies without incurring significant additional computational costs should be explored as an alternative, and outputs stored from future simulations should include the required quantities.

Ray tracing: With currently available ray tracing algorithms (see e.g (49)), it is computationally infeasible to cover both the large volume required by future weak lensing surveys, and yet maintain the accuracy at small scales required for strong lensing. Therefore, we must develop a multi-resolution raytracing algorithm that will effectively cover the two regimes.

Baryonic effects: Baryonic feedback effects are known to alter the local matter density and hence the weak lensing observables (50; 51). This is one of the leading systematic effects in cosmic shear analyses that is limiting us from extracting information from small scale measurements (52). These effects must be included in the modeling for future analyses. While attempts have already been made in some existing hydrodynamical simulations, the predictions vary significantly due to our lack of understanding of the relevant astrophysical processes.

Expected Scientific Returns

We envision that these simulations will have a variety of usages. Firstly, a high-resolution simulation that includes correlated astrophysical signal and systematics could be used as a validation tool of the analysis pipelines. Simulated skies generated in this way can be treated as data, and pipelines could be validated by testing whether the true input cosmology is recovered. Secondly, if enough realizations are generated, the simulations can be used to estimate the covariance between the probes to small scales. Finally, in conjunction with the points above, the simulations can be used as forecasting tools to estimate the signal-to-noise ratio of a given probe in realistic settings. The simulations will be especially useful for statistical measurements that are difficult to model analytically, such as when we move towards higher-order clustering statistics and extracting information from nonlinear scales.

Summary

In the next decade, exciting discoveries will be made by combining data sets from large-scale structure, CMB and line intensity mapping experiments. In preparation, we must develop tools to conduct these analyses such as simulations with correlated observables. Despite their importance, resources in developing these simulations have been scarce since a) they do not belong to a specific collaboration/telescope, and b) to generate fully coherent simulations, expertise from various areas are required. In this letter, we have described why these simulations are needed, listed a few observables that we intend to implement, and highlighted a few areas that require technical development.

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