Snowmass2021 Letter of Interest:
Higher-order statistics with 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
■ (CF7) Cosmic Probes of Fundamental Physics
■ (TF9) Astro-particle physics & cosmology
■ (CompF2) Theoretical Calculations and Simulation
■ (CompF3) Machine Learning

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Abstract:

The most stringent constraints on cosmology will not only come from a combination of cosmological probes, but also complementary methods *within* each probe. While second-order statistics have been the default method in analyzing cosmological data to date, higher-order statistics are expected to unveil new cosmological and astrophysical information and enable us to calibrate various systematic effects. They will be particularly powerful with high-precision cosmological surveys that probe deep into the small, nonlinear scales, such as Vera Rubin Observatory LSST, DESI, Euclid, Roman Space Telescope, Simons Observatory and CMB-S4. This letter supports the development of higher-order statistics for these upcoming surveys. We summarize the main observables that will greatly benefit from the application of high-order statistics: weak gravitational lensing, galaxy distributions, cosmic microwave background (CMB) lensing, and thermal and kinematic Sunyaev-Zel'dovich effects. We outline the key areas that need to be developed to realize their potentials: numerical simulations, systematic effects, and machine learning tools.

Second-order statistics—the two-point correlation function or its Fourier transform, the power spectrum—can capture the information content in a field fully *only* if the field is Gaussian. They have been the default method for Stage-III surveys [1–4]. However, the growth of structure is highly nonlinear on small scales ($\lesssim$10 Mpc) at late times ($z \lesssim 2$), resulting in highly non-Gaussian density fields. In this regime, effects of dark energy and massive neutrinos are the strongest, motivating studies beyond the second-order statistics.

Key Obsevables:

Weak lensing of galaxies: by measuring the distortion in shapes of background galaxies, one can infer the distribution of the intervening matter. Three-point functions, expected to be zero for a Gaussian field, have been measured to be non-zero [5–8]. Weak lensing summary statistics, such as peak counts [9–24], minimum counts [24;25], Minkowski functionals [26–30], higher-order moments [19;29;31–36], and scattering transform [37], can be simpler to measure than three-point functions and also contain information of all orders. The most well-studied summary statistic, peak counts, has already yielded constraints comparable to those from the second-order statistics with Stage-II and III surveys [14;15;18;20;21]. Altogether, weak lensing higher-order statistics are predicted to be more powerful than two-point statistics in constraining dark energy and neutrino mass M_ν for Stage-IV surveys, although many challenges (see below) must be overcome before this can be achieved.

Galaxy clustering: constraints from second-order statistics of galaxy clustering are severely limited by parameter degeneracies among the cosmological parameters and galaxy bias. Higher-order statistics, such as the bispectrum, can break these parameter degeneracies and more tightly constrain cosmological parameters [38–41]. If we include galaxy clustering on nonlinear scales, the improvement over second-order statistics can be even greater, e.g. a 1.8 $\times$ improvement on M_ν with Planck priors for $k_{\max} = 0.5\, h/\mathrm{Mpc}$ [41].

CMB lensing: CMB lensing uses the CMB last-scattering surface as the back light. The signal is rather Gaussian because photons are deflected multiple times along the line-of-sight and most of the lensing is caused by mostly linear structures at redshift $z \simeq 2$ [42]. Still, CMB lensing measurements have progressed rapidly and forecast studies have shown that a non-Gaussian signal can be detectable with Stage-III surveys [43] and at the 50σ level with CMB-S4 [44]. Related phenomena such as the moving lens and Rees-Sciama effects are similarly anticipated to be observable [45–47].

Thermal Sunyaev-Zel'dovich (tSZ): the tSZ effect probes the integrated pressure of free electrons predominantly in galaxy groups and clusters. It has been shown that tSZ statistics beyond the power spectrum, such as higher-order moments [48;49], bispectrum [50–54], and one-point PDF [52;53;55;56], contain a significant amount of cosmological information beyond that contained in cluster counts (for current SNR thresholds) or the power spectrum. The tSZ signal is biased towards electrons in high-mass halos and hence is particularly sensitive to the amplitude of fluctuations σ_8. Combining tSZ statistics of different orders is particularly powerful in breaking degeneracies between σ_8 and parameters that quantify the intracluster medium physics [49].

Kinematic Sunyaev-Zel'dovich (kSZ): the kSZ effect is sensitive to the gas content and profile of galaxies, as well as the velocity fields they follow. Velocity measurements provide unique access to the largest scales [57], which hold key information about scale-dependent effects such as primordial non-Gaussianity [58] and isocurvature [59], along with phenomena including CMB anomalies [60], modified gravity [61], and subtle general relativistic corrections [62]. Extracting the kSZ effect from combining CMB temperature and galaxies requires mixed bispectrum estimators. Most kSZ estimators in the literature contain one power of CMB temperature and two powers of the galaxy field [63]. However, the option with two powers of CMB temperature and one of the galaxy density has been explored [64–66] and is particularly well suited for photometric galaxy samples.

Challenges and Opportunities:

Simulations: higher-order statistics probe deep into the nonlinear scales of the matter and galaxy fields, where analytic theories become insufficient. Therefore, the theoretical modeling of the cosmological dependence of the signal and the error estimation will need to rely on numerical simulations. An increasing number of simulation suites specifically tailored for developing higher-order statistics have been recently completed and used to forecast for upcoming surveys[67–72]. They also serve as excellent training sets to further test and calibrate novel methods. With a significant increase in statistical precision expected from Stage-IV experiments, a new series of simulations that extend a wide range of cosmological models, cover a large volume, and accurately implement small scale astrophysical effects will be critical. These efforts will also benefit greatly from accelerated N-body codes and approximate methods[73–79], as well as generative neural networks[80–84].

Systematic Effects: astrophysical effects and survey systematics, if unaccounted for, can bias the inference on cosmological parameters. Major systematic effects, such as baryonic feedback[85], intrinsic alignment of galaxies[86–89], photometric redshifts[90–93], and galaxy shape measurement biases[94], have been studied intensively for second-order statistics, but less so for higher-order statistics. Early works on the impact of systematics on higher-order statistics [24;25;95–97] have shown that these statistics are either less affected by systematics, or biased in a different direction than those from second-order statistics, indicating that they can also serve as a tool to calibrate systematic effects. In addition, kSZ observations will provide unique constraints on the distribution of baryons, and in turn help all the second-order statistics that probe the small, nonlinear scales.

Machine Learning: alternative to pre-defined statistics, machine learning tools can learn from the data optimal reduced representations[98]. In the context of weak lensing, neural networks extract more information than pre-defined second- or higher-order statistics from simulated data[99–102], even in the presence of noise[103]. A recent application of a neural network to KiDS-450 weak lensing maps has already led to improved cosmological constraints[104], though their simple treatment of systematics is likely insufficient for future deeper surveys. Deep networks have also been used to do inference with simulated 3D matter density[105;106] and the reconstructed CMB lensing potential[107]. A major outstanding issue is to interpret the results from neural networks and to understand the origin of their information, work on which has only recently begun[108–110]. Further work is needed to build interpretable models that are also robust to the effect of systematic effects.

Summary:

There is rich information stored in galaxy, lensing, and CMB higher-order statistics. Theoretical works have predicted significant gains in cosmological constraints when these higher-order statistics are applied to cosmological observables. In addition, they can also provide new insights to astrophysical and survey-related systematics, serving as a calibration tool to existing second-order statistics. To achieve maximal returns from Vera Rubin Observatory LSST, DESI, Euclid, Roman Space Telescope, Simons Observatory, and CMB-S4 with higher-order statistics, we need to invest in developing advanced numerical simulation methods and thoroughly study related systematic effects. These efforts will in turn contribute to the already well developed second-order statistical tools by pushing them into smaller, nonlinear scales. They will also benefit the development of innovative techniques including novel statistical methods and machine learning tools.

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