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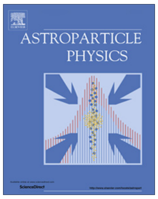

Growth of cosmic structure: Probing dark energy beyond expansion

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ABSTRACT

The quantity and quality of cosmic structure observations have greatly accelerated in recent years, and further leaps forward will be facilitated by imminent projects. These will enable us to map the evolution of dark and baryonic matter density fluctuations over cosmic history. The way that these fluctuations vary over space and time is sensitive to several pieces of fundamental physics: the primordial perturbations generated by GUT-scale physics; neutrino masses and interactions; the nature of dark matter and dark energy. We focus on the last of these here: the ways that combining probes of growth with those of the cosmic expansion such as distance-redshift relations will pin down the mechanism driving the acceleration of the Universe.

One way to explain the acceleration of the Universe is invoke dark energy parameterized by an equation of state w. Distance measurements provide one set of constraints on w, but dark energy also affects how rapidly structure grows; the greater the acceleration, the more suppressed the growth of structure. Upcoming surveys are therefore designed to probe w with direct observations of the distance scale and the growth of structure, each complementing the other on systematic errors and constraints on dark energy. A consistent set of results will greatly increase the reliability of the final answer.

Another possibility is that there is no dark energy, but that General Relativity does not describe the laws of physics accurately on large scales. While the properties of gravity have been measured with exquisite precision at stellar system scales and densities, within our solar system and by binary pulsar systems, its properties in different environments are poorly constrained. To fully understand if General Relativity is the complete theory of gravity we must test gravity across a spectrum of scales and densities. Rapid developments in gravitational wave astronomy and numerical relativity are directed at testing gravity in the high curvature, high density regime. Cosmological evolution provides a polar opposite test bed, probing how gravity behaves in the lowest curvature, low density environments.

There are a number of different implementations of astrophysically relevant modifications of gravity. Generically, the models are able to reproduce the distance measurements while at the same time altering the growth of structure. In particular, as detailed below, the Poisson equation relating over-densities to

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gravitational potentials is altered, and the potential that determines the geodesics of relativistic particles (such as photons) differs from the potential that determines the motion of non-relativistic particles. Upcoming surveys will exploit these differences to determine whether the acceleration of the Universe is due to dark energy or to modified gravity.

To realize this potential, both wide field imaging and spectroscopic redshift surveys play crucial roles. Projects including DES, eBOSS, DESI, PFS, LSST, *Euclid*, and *WFIRST* are in line to map more than a 1000 cubic-billion-light-year volume of the Universe. These will map the cosmic structure growth rate to 1% in the redshift range $0 < z < 2$, over the last 3/4 of the age of the Universe.

1. Introduction: why measuring growth is interesting

The standard cosmological model posits that the largest structures that we observe today – galaxies and clusters of galaxies – grew out of small initial fluctuations that were seeded during the phase of inflationary expansion, some 10^{-35} s after the Big Bang. Subsequently these fluctuations grew under the influence of gravity. Most of the growth occurred after the decoupling of photons and electrons, some 350,000 years after the Big Bang, when photons cease to be coupled to baryons and provide pressure support against gravitational collapse. The Jeans mass – smallest mass that can undergo gravitational collapse – therefore drastically drops at decoupling. This, as well as the fact that the Universe was mostly matter-dominated at that point, allows the galactic-size structures to grow unimpeded.

In the currently favored cosmological model, where most of the matter budget is dominated by the slow-moving massive particles (the "cold dark matter" or CDM), the smaller structures form first, while the largest structures form the latest. Therefore, objects that are of the most interest to cosmologists, galaxies and clusters of galaxies, form at recent times and, in some cases, are still forming today. Hence, observations in various wavelengths can probe the full evolution of the formation of structure in the Universe, from when the first objects formed until today.

Observations of the growth of structure provide a wealth of information about dark matter and dark energy. In particular, the scaling of the amplitude of growth vs. cosmic time – the so-called growth function – sensitively constrains dark energy parameters in a way that is complementary to distance measurements. The temporal evolution of the growth is now readily observed by measuring the clustering of galaxies at multiple redshifts, and in the near future gravitational lensing has the potential to measure the same quantity but with the added advantage that it is directly sensitive to the growth of dark matter structures (as opposed to galaxies or other baryonic tracers such as hydrogen in the inter-galactic medium). Additionally, the number counts of clusters of galaxies, as a function of their mass and redshift, provide another excellent probe of cosmological parameters. Our ability to observe and model both the growth and the cluster counts have significantly matured over the past decade, and these two probes now provide constraints on dark energy that are complementary to distance measurements by type Ia supernovae, baryon acoustic oscillations (BAO; which encode geometrical aspects of the clustering of galaxies), and the cosmic microwave background (CMB).

Over the next 10–20 years, we expect a wealth of new observations that include ground imaging surveys (e.g. DES and LSST), redshift surveys (e.g. eBOSS, PFS and DESI) and space surveys (e.g. *Euclid* and *WFIRST*). The combination of these observations will provide high-precision measurements of the growth of structure out to redshift of a few and across most of the sky. These measurements will, in turn, strongly constrain the equation of state of dark energy and, more generally, the expansion history of the Universe (discussed in the Snowmass-2013 paper on Distances [1]) over the past ∼10 billion years.

The growth of structure is particularly sensitive as a probe of modified-gravity explanations for the accelerating Universe, and has already been used to impose constraints on the extensions of, and modifications to, General Relativity (GR). The effectiveness of the growth of structure in this regard is maximized when it is combined with distance measurements, which can be understood as follows. Modified-gravity models are constructed so that they reproduce distances consistent with their current measurements which, in the context of GR, indicate an accelerating universe. Importantly, these models generally predict the growth-of-structure history that is different from the GR prediction given those same distance measurements. Therefore, independent precision measurements of the growth of structure test whether GR adequately describes the late-time expansion of the Universe. Such tests are paramount to our understanding of dark energy and may lead to fundamental discoveries of physics at large scales, and this makes the growth of structure a very important probe of the Universe.

Good complementarity, redundancy, and control of the systematic errors are keys in making the growth of structure observations reach their full potential. Photometric and spectroscopic surveys are particularly complementary in various aspects of their observational strategies; moreover, spectroscopic surveys play an additional key role of calibrating the photometric redshifts obtained from galaxy colors. Multiple observations of the same sky coverage may be useful for this reason, while non-overlapping observations help reduce cosmic variance. Finally, numerical (*N*-body) simulations have an extremely important role of providing theoretical predictions for the growth of structure in the quasi-linear regime (roughly 10–50 megaparsecs) and especially in the non-linear regime (scales less than about 10 megaparsecs).

The paper is organized in follows. In Section 2 we define what precisely we mean by the growth of structure, and broadly illustrate constraints on it from future surveys. In Section 3 we discuss how the growth of structure probes the dark-energy and modified-gravity explanations for the acceleration of the Universe. In Section 4 we discuss in some detail several of the most promising probes of the growth of structure – clustering of galaxies in spectroscopic surveys, counts of galaxy clusters, and weak gravitational lensing. Finally in Section 5 we discuss the very important role of simulations in theoretically predicting growth on non-linear scales.

2. Preliminaries and definitions

In the linear theory – valid at sufficiently early times and sufficiently large spatial scales, when the fluctuations in the matter energy density ρ_M are much less than unity – the matter density contrast $\delta(t) = \delta\rho_M/\rho_M$ evolves independently of the spatial scale k. The growth of fluctuations in time (well within the Hubble radius) $\delta(t)$ can be obtained by solving the equation