Snowmass2021 - Letter of Interest

Large-Scale Structure at high redshift: a probe of fundamental physics

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

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Abstract: Advances in experimental techniques make it possible to map the $z > 2$ Universe at high fidelity in the near future. This will increase the observed volume by many-fold, while providing unprecedented access to very large scales, which hold key information about primordial physics. Recently developed theoretical techniques, together with the smaller size of non-linearities at high redshift, allow the reconstruction of an order of magnitude more "primordial modes", and should improve our understanding of the early Universe through measurements of primordial non-Gaussianity and features in the primordial power spectrum. In addition to probing the first epoch of accelerated expansion, such measurements can probe the Dark Energy density in the dark matter domination era, severely constraining broad classes of dynamical Dark Energy models. The shape of the matter power spectrum itself has the potential to detect sub-percent fractional amounts of Early Dark Energy to $z \sim 10^5$, probing Dark Energy all the way to when the Universe was a only a few years old. The precision of these measurements, combined with CMB observations, also has the promise of greatly improving our constraints on the effective number of relativistic species, the masses of neutrinos, the amount of spatial curvature and the gravitational slip.

The inhomogeneous Universe, as probed by fluctuations in the cosmic microwave background (CMB) radiation or surveys of large-scale structure (LSS), provides one of our best windows on fundamental physics at ultra-high energies. Continuous advances in detector technology and experimental techniques are pushing us into a new regime, enabling mapping of large-scale structure in the redshift window $2 < z < 6$ using both relativistic and non-relativistic tracers. This will allow us to probe the metric, particle content and *both* epochs of accelerated expansion (Inflation and Dark Energy domination) with high precision.

Cosmological constraints from the CMB and LSS are well developed and can be accurately forecast. They include constraints on the expansion history and curvature [1], primordial non-Gaussianity [2], features in the power spectrum (primordial [3] or induced [4;5]) or running of the spectral index [6;7], dark energy in the approach to matter domination [8], dark matter interactions [9], light relics and neutrino mass [10;11] and modified gravity [12;13]. While we do not know from theory which of these many probes is most likely to turn up evidence of new, beyond standard model, physics; well understood phenomenology allows us to forecast where our sensitivities will be highest and our inference cleanest. To work where the inference is cleanest and the noise lowest we should push to high redshift.

Moving to higher redshift allows us to take advantage of four simultaneous trends. (1) A wider lever arm in redshift leads to rotated degeneracy directions, tightening constraints. (2) The volume on the past lightcone increases dramatically, leading to much tighter constraints on sample-variance limited modes and a longer lever arm in scale. (3) The degree of non-linearity is smaller, and the field is better correlated with the early Universe and less affected by astrophysical processes. (4) Very high precision perturbative models built around principles familiar from high-energy particle physics become increasingly applicable. Indeed at high redshift, with large volume surveys, we increasingly probe long wavelength modes which are linear or quasi-linear and carry a great deal of 'unprocessed' information from the early Universe.

Quantifying the amount of information about the initial conditions that is available using modern perturbative techniques will be one of the key goals of the white paper. Non-linear evolution, astrophysical processes and noise cause decorrelation with the initial conditions and hence loss of information on small scales. The effective number of modes that are correlated with the initial conditions is shown in Figure 1, left panel. Extending observations to $z \gtrsim 3.5$ has the potential to probe more 'primordial' modes than the CMB on the same footprint, due to the inherent 3-dimensional nature of LSS surveys. Since the Fisher matrix for most primordial physics parameters scales as $N_{\rm modes}$, this can be used as a "Primordial Physics Figure of Merit" to compare different experiments. In the white paper, we will explore the consequences for constraining early-Universe physics from the billions of linear or quasi-linear modes that are available (in principle) to a high redshift large-scale structure survey.

We also note that observing the high-z universe through measurements of the LSS can be transformative in our study of Dark Energy. There are three main reasons for this, listed below:

1) Direct measurement of the expansion history over the observed redshift range: broad classes of dynamical Dark Energy exhibit "tracking behaviour" with respect to the dominant energy density at a given redshift [14], making measurements of the Dark Energy density during the transition into matter domination at $z \gtrsim 2$ particularly compelling. A combination of Baryon Acoustic Oscillations (BAO) and Redshift-Space Distortions (RSD) can directly obtain the Dark Energy density over the redshift range of observations [6;15], thus severely constraining wide classes of models that mimic a cosmological constant at later times.

2) Degeneracy breaking: the parameter sensitivity varies considerably with redshift, and combining measurements over a wide redshift range can very effectively break degeneracies internally [16]. This includes distinguishing the effects of dynamical Dark Energy and neutrino masses or other particles.

3) Indirect probe of early Dark Energy (EDE) to very high redshift: changes in the expansion rate at high z temporarily alter the growth of structure and manifest themselves as features in the measured

power spectrum[4;17;18]. By observing a very large volume, we can measure the shape of the power spectrum to an unprecedented accuracy (due to the reduced cosmic variance), and hence dramatically improve our sensitivity to EDE (and light relics, as probed by $N_{\rm eff}$ [19]). Forecasted bounds on the maximum fraction of allowed Early Dark Energy $f_{\rm EDE}$ when mapping the $z > 2$ Universe are shown in the right panel of Figure 1, as a function of critical z_c, approximately the redshift of maximum EDE (fractional) density. Quite excitingly, next-generation LSS surveys can constrain the fraction of EDE to be below 1% all the way to $z \sim 10^5$, making them precision Dark Energy probes throughout most of cosmic history.

While it is not our goal to advocate for a particular observational approach, we will mention that there are two major tracers of large-scale structure for which we can make spectroscopic observations with next-generation facilities. First, building upon deep imaging from LSST[20] and Euclid[21], we could target Lyman Break Galaxies. These galaxies are abundant, well studied and well understood, representing massive, actively star-forming galaxies with a luminosity approximately proportional to their stellar mass. A sizeable fraction have bright emission lines which could facilitate obtaining a redshift[22]. Secondly, the majority of the baryonic matter in the Universe is in the form of Hydrogen. Neutral hydrogen, predominantly in galaxies, emits through the 21 cm hyperfine, magnetic dipole, transition. This line is weak and at long wavelength, requiring large collecting area to detect it, but there is little absorption or confusion if the line can be detected[7;8].

At the same time, the noise on CMB lensing maps from future wide-field experiments such as the Simons Observatory[23] and CMB-S4[9] will be reduced by more than one order of magnitude. While CMB lensing alone mostly provides information that is projected along the line-of-sight (and with a broad redshift kernel), its cross-correlation with the LSS in several redshift bins (CMB lensing tomography),[24] can break the degeneracy with galaxy bias and provide measurement of the amplitude of perturbations as a function of redshift, which directly leads to tighter constraints on neutrino masses and Dark Energy, while mitigating some of the possible systematics[9;22;24]. Moreover, comparing the motion of non-relativistic matter through redshift-space distortions to the deflection of CMB photons will put some of the most informative bounds on theories of modified gravity[12]. Finally, the cross-correlation of LSS with CMB lensing can potentially improve the robustness of constraints relying on the ultra-large scales, such as measurements of local non-Gaussianity[25].

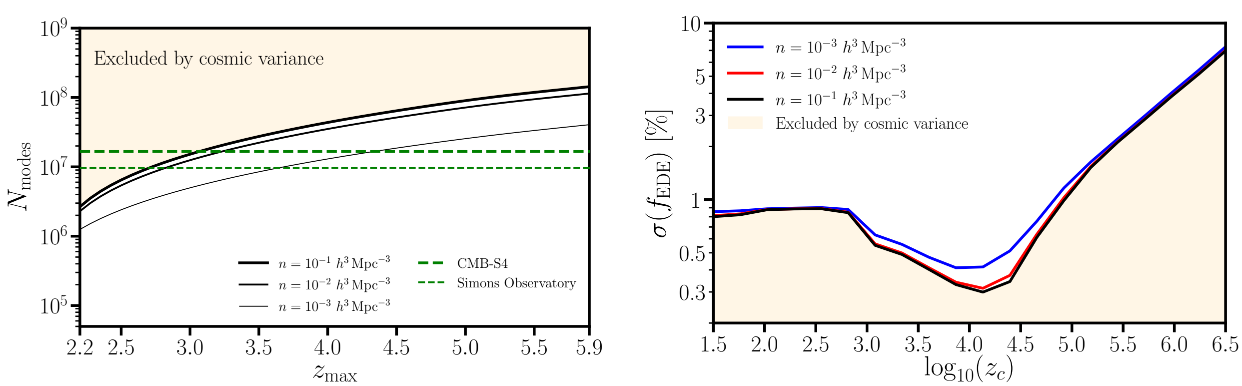

Figure 1: **Left panel:** Effective number of modes that are correlated with the initial conditions. While large scales are highly correlated with the initial conditions, on small scales shot noise and non-linearities cause decorrelation, and those modes are not counted here. Extending observations to $z \gtrsim 3.5$ can probe more primordial modes than even future CMB experiments. **Right panel:** Maximum fractional amount of early Dark Energy $f_{\rm EDE}$ as a function of critical redshift z_c (approximately the redshift at which the contribution is maximal). Future LSS experiments can constrain $f_{\rm EDE}$ to sub-percent all the way to $z_c \sim 10^5$.

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