Astro2020 Science White Paper

Dark Energy and Modified Gravity

Thematic Areas: Cosmology and Fundamental Physics

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Endorsing Collaborations: The surveys designed to carry out dark energy and cosmology investigations in the next decade have attracted large collaborations, organized to facilitate many diverse science goals and broad participation within unified data sets. The following collaborations involving over a thousand people are co-signing this white paper to endorse its content, having reviewed it following their respective internal management processes:

- The Dark Energy Spectroscopic Instrument Collaboration (DESI),
- The Euclid Consortium,
- The LSST Dark Energy Science Collaboration (LSST-DESC),
- The Simons Observatory Collaboration (SO),
- The WFIRST Cosmology Science Investigation Teams

Abstract:
Despite two decades of tremendous experimental and theoretical progress, the riddle of the accelerated expansion of the Universe remains to be solved. On the experimental side, our understanding of the possibilities and limitations of the major dark energy probes has evolved; here we summarize the major probes and their crucial challenges. On the theoretical side, the taxonomy of explanations for the accelerated expansion rate is better understood, providing clear guidance to the relevant observables. We argue that: i) improving statistical precision and systematic control by taking more data, supporting research efforts to address crucial challenges for each probe, using complementary methods, and relying on cross-correlations is well motivated; ii) blinding of analyses is difficult but ever more important; iii) studies of dark energy and modified gravity are related; and iv) it is crucial that R&D for a vibrant dark energy program in the 2030s be started now by supporting studies and technical R&D that will allow embryonic proposals to mature. Understanding dark energy, arguably the biggest unsolved mystery in both fundamental particle physics and cosmology, will remain one of the focal points of cosmology in the forthcoming decade.

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1 Introduction

Twenty years since the discovery of cosmic acceleration, the laws of physics on the largest scales remain an enigma. The phenomenon continues to drive us to consider bold transformations in our understanding of cosmic forces. Broadly speaking, theories of dark energy fall into three major classes. The first and simplest class is the cosmological constant, which fits all the available data but which is theoretically unsatisfactory because it is fine-tuned and sensitive to the UV completion of gravity. This implies that any fundamental theory that could give rise to a stable value must have some new physics associated with it [1, 2].

The second class of models includes quintessence-type theories where dark energy is a component with novel properties, typically explained in terms of a scalar field. These models of dark energy are the simplest dynamical models of dark energy and are a low-redshift equivalent of inflation [3]. They have recently been discussed within a somewhat controversial debate about the swampland conjecture, which states that theories that can produce a slowly rolling $w \simeq -1$ universe like the one we observe do not have consistent UV completions within string theory ([4], but see also [5]). This conjecture severely constrains the space of string-theory compatible models [6, 7].

The third class of models includes modified-gravity theories in which cosmic acceleration is caused by some extension of the gravitational sector. These theories have been significantly constrained after the discovery of gravitational wave source GW170817 for which the optical counterpart has been discovered, which constrained the speed of tensor mode propagation $c_t = c$ with a fractional accuracy of 10^{-15}. Nevertheless, there are significant caveats: i) the cosmic acceleration and the LIGO event are separated by twenty orders of magnitude in energy scales and the effective theories can be very different [8], and ii) modified-gravity theories can predict significant time dependence, so a single event cannot completely constrain the underlying physics. Significant parts of parameter space thus remain open. Finally, there are somewhat more exotic theoretical paths towards generating accelerated expansion, like novel coupling between baryons and dark matter [9] or involving neutrino physics [10, 11].

The main observables that will help us distinguish between these scenarios are the precise characterization of the *expansion history*, the *gravitational slip* ($\eta = \Phi/\Psi$, where Φ and Ψ are gravitational potentials in the time and space perturbations of the metric) and the *effective large-scale Newton's constant* $G_{\rm eff}$ [12]. Both η and $G_{\rm eff}$ are unity in the standard GR, but can be time- and scale-dependent quantities in modified-gravity theories. This has led to renewed interest in measuring the growth of structure and the combination of datasets with the explicit purpose of constraining these two parameters [13–20]

Faced with this compelling mystery, astrophysicists have mounted an ambitious multi-faceted campaign to study the behavior of the Universe on the large scales. This program has been undeniably successful: data quality has improved radically over the past decade, with new leaps expected early in the 2020s from the upcoming facilities. There have been major improvements in parameter constraints: for a simple equation of state $w(z) = p/\rho c^2$, we have measured a constant w to be consistent with the cosmological constant ($w = -1$) to about ±0.05. And while there is consistency in many aspects of the results, there are also active disagreements in other parts, such as the value of the Hubble constant and perhaps the amplitude of late-time matter clustering [21–26].

2 Entering the decade of precision dark energy science

There is a rich portfolio of observational methods that we expect will drive the study of cosmic acceleration in the coming decade. We stress that the whole is more than the sum of the parts. The methods reinforce each other both in terms of statistical leverage and control of systematic uncertainties. Cross-correlations and data combination have emerged as indispensable tools for both controlling systematic uncertainties and isolating particularly informative aspects of theories. During this decade, use of blinded analysis has become the norm for most measurements of cosmic acceleration, so as to avoid confirmation bias; developing methods for blinded analysis that will work for surveys at the next level of precision will be important as the field moves forward. For all of these methods, marginalizing over systematic uncertainties has resulted in expanded parameter spaces, and the field continues to work on building and validating models for major systematic uncertainties that will work at the level needed for upcoming surveys.

There are two main classes of methods to study dark energy. The first measures the *expansion history*, particularly through the study of the distance-redshift relation. The second class measures the *growth* of matter density fluctuations, which is impacted by the large-scale gravitational forces. Because dark energy is typically smooth, it slows the growth of fluctuations and decreases the number of dark matter halos of a given mass. However, growth measurements offer more than an increase in statistical precision; they provide an important consistency check. In a broad class of quintessence theories, the expansion history predicts the behavior of the growth of fluctuations, so any evidence for inconsistency there would necessarily imply some non-standard physics in the gravitational sector.

We now briefly summarize what we see as the major methods for the coming decade.

Expansion history

Baryonic Acoustic Oscillations (BAOs): Description: The BAO peak is a feature in the correlation function of a tracer of large-scale structure, acting as a standard ruler and thus allowing measurements of distances and expansion rates as a function of redshift. Status: Numerous experiments have measured BAOs with high precision in the past decade, including 2dFGRS, 6dFGS, WiggleZ, SDSS II, BOSS and eBOSS, using both galaxies and the Lyman-α forest as tracers. In the 2020s, DESI, PFS, and Euclid will carry out high precision galaxy BAO measurements to $z \sim 2$ with DESI Lyman-α, HETDEX, and WFIRST galaxy surveys reaching $z \sim 3$. Future challenges: The main future challenge lies in obtaining sufficiently large spectroscopic samples at ever increasing volumes. At redshifts beyond 2, non-galaxy tracers such as the Lyman-α forest and 21 cm could be optimal. Unique selling points: BAO is arguably the most mature method and is theoretically and experimentally well understood.

Supernovae Type Ia (SNe Ia): Description: Type Ia supernovae (SNe Ia) are bright standard candles that probe the expansion history of the Universe through calibrating the luminosity distance as a function of redshift. Status: The CfA Supernova program, Carnegie Supernova Program (CSP), SDSS-II SN survey, Supernova Legacy Survey (SNLS), PanSTARRS, DES Supernova program, ESSENCE, GOODS survey, CANDELS/CLASH, Supernova Cosmology Project (SCP) and others have measured SNe Ia over wide range of redshifts. In the 2020's, LSST will deliver $O(10^5)$ photometric SNe Ia, WFIRST will measure SNe Ia in the infrared with the resolution and photometric stability achievable from space, while the Foundation survey will yield many low-redshift SNe. Future challenges: Photometric SNe require very precise photometric and filter calibrations, spectroscopic characterization and updated light curve models. Unique selling points: SN are the dominant probe of the Hubble diagram at the lowest redshifts, $z < 0.5$, but are also bright enough to be used over a wide range of redshift.

Time delays strong lensing: Description: Time delays measured between the multiple images of the same object provide measurements of the Hubble parameter independently of other distance measures. Status: Dedicated observational programs like H0LiCOW/COSMOGRAIL and STRIDES, which combine ground and space observations of 20 lensed quasar systems, are publishing competitive H_0 constraints. Future surveys like LSST will discover orders of magnitude more systems, with $\sim$400 expected to be suitable for dark energy science, and measure hundreds of strongly gravitationally-lensed supernovae, which should enable similar measurement with less monitoring. Future challenges: Mass modeling, external convergence, and correlations between the modeling and the cosmological parameters remain the largest systematic uncertainty. Unique selling points: This technique is independent from other distance indicators and can achieve precision to constrain dark-energy parameters from a relatively small number of systems.

Standard Sirens: Description: Gravitational waves (GW) from the inspiral of two massive objects are a powerful measure of a source's luminosity distance. Status: The discovery of GWs by Advanced LIGO in 2016 ushered in the era of gravitational wave astrophysics. From one source with an identified optical counterpart, a 7% measurement of the Hubble constant was obtained. The 2020s could see standard sirens providing a 2% determination of H_0.
Future challenges: As more sources are discovered, selection effects in both the GW surveys and the EM follow-up programs will need to be included in systematic error analyses.
Unique selling points: The amplitude of the standard siren signal is computed from fundamental physics and does not rely on empirical calibration.

Growth

Weak Gravitational Lensing: Description: Measurements of coherent distortions in galaxy shapes due to weak gravitational lensing reveal the distribution of dark matter in the Universe. Status: Dedicated surveys including CFHTLS, KIDS, DES and HSC have achieved statistical precision of a few percent in the amplitude of matter fluctuations at redshift $z \lesssim 1.2$. Lensing surveys in the 2020s from the ground (LSST) and space (WFIRST and Euclid) will cover large sky areas at significant depths. Dedicated space-based observations will enable major advances via high resolution, wavefront stability, and access to the NIR. Future challenges: Photometric redshifts and blending will require further methodological improvements. Another challenge is the theoretical modeling of the signal in the presence of astrophysical systematics (intrinsic alignments and baryonic effects). Unique selling points: Combining tomographic measurements of weak lensing with measurements of the expansion history may be the most effective way to probe GR potentials and distinguish between dark energy and modified gravity.

Cosmic Microwave Background (CMB) lensing: Description: Measuring distortions in the CMB fluctuations can probe weak gravitational lensing to the surface of last scattering. Status: Lensing reconstructions from the Planck satellite currently provide the highest signal-to-noise measurements on the linear amplitude of fluctuations at $z < 6$. Simons Observatory, CMB-S4 and PICO will improve these limits by an order of magnitude in the coming decades.
Future challenges: In order to minimize systematic uncertainties from secondary anisotropies, the CMB lensing will rely on the polarization signal, which is weaker and has its own, yet to be fully understood foregrounds. Unique selling points: CMB lensing provides a long redshift lever-arm

and has fewer observational systematic uncertainties compared to galaxy lensing.

Peculiar Velocities: Description: Peculiar velocities are motions of galaxies not comoving with the expansion of the Universe. They can be measured for individual objects using redshift and a distance indicator. Status: 6dFGS and 2MTF have measured tens of thousands of galaxy peculiar velocities with accuracies of 20%. Supernova surveys have higher precision, but are limited by low numbers. Upcoming surveys like TAIPAN, WALLABY+WNSHS, ZTF and LSST will make large peculiar-velocity catalogs, enabling tight constraints on growth at low redshift. Future challenges: Proper handling of the asymmetric uncertainties on distance indicators is crucial. Unique selling points: Understanding the local peculiar velocity field constrains dark energy and dark matter directly, and helps with systematic control in other probes by characterizing the local density environment.

Redshift-space distortions (RSDs): Description: Redshift-space distortions are peculiar velocities detected statistically as an apparent anisotropy of the measured correlations in any large-scale structure survey. Status: Spectroscopic galaxy surveys, including 6dFGS, WiggleZ, VIPERS, BOSS and eBOSS, have measured the growth parameter $f\sigma_8$ with 3-10% precision depending on modeling assumptions. In the coming decade DESI, PFS, Euclid and WFIRST will make percent-level measurements at $z < 1.8$ and WFIRST will push to $z \simeq 3$. Future challenges: Theoretical modeling of non-linear effects, and the connection between light and mass, remain the main issue. Unique selling points: One of the most direct ways of measuring the growth rate with the potential to significantly improve signal-to-noise with better modelling.

Kinetic Sunyaev-Zeldovich (kSZ) effect: Description: The kSZ effect is the Doppler shift of CMB photons caused by scattering off the plasma in late-time galaxies and clusters. Status: The first detection of the pairwise kSZ was made in 2012 using data from the Atacama Cosmology Telescope and BOSS galaxy survey. This science will benefit from the large survey area CMB experiments (SO, CMB-S4, PICO), and their cross-correlation with optical galaxy surveys (LSST, DESI). Future challenges: A difficulty in constraining growth using kSZ measurements is the degeneracy with the optical depth in galaxy clusters and groups. Unique selling points: This is an independent probe of the velocity field at low redshift, with different systematics and modelling assumption compared to redshift-space distortions.

Galaxy Clusters: Description: Galaxy clusters are the most massive, gravitationally bound structures in the Universe, and their abundance provides a sensitive probe of growth. Status: Planned optical/IR (LSST, WFIRST, Euclid), Sunyaev-Zeldovich (SO, CMB-S4, PICO), and X-ray (eROSITA, ATHENA) surveys will provide cluster catalogs over a wide range in mass and out to unprecedentedly high redshifts. Future challenges: The main difficulty is obtaining an accurate absolute cluster mass calibration and precise relative mass estimates. The latter are considerably improved using X-ray data; while eROSITA will provide these at relatively low redshifts, an ongoing source of high-throughput, targeted X-ray observations will be required to fully exploit the high-redshift catalogs provided by thermal SZ surveys. Unique selling points: Galaxy clusters are a statistically sensitive probe of growth with largely independent systematics.

3 Conclusions and Outlook

The coming decade will be an exciting one for dark energy studies, as a new generation of powerful observational facilities comes to fruition. The combination of high-precision data with growth in theoretical models and statistical techniques will allow a great leap in our cosmological leverage, testing our theories in unprecedented ways and perhaps sharpening the fault lines in present results. As we look toward the coming decade in cosmology and the study of dark energy and modified gravity, we want to highlight the following themes.

Improving statistical and systematic precision on the equation of state is essential. The current statistical precision for the wCDM model is around 5% (1 σ). To formally distinguish between a $w = -1$ model and a $-1 < w < 0$ model at 1:100 statistical odds, one would need to achieve sub-percent level precision. Even more importantly, dark energy models with dynamical equations of state remain significantly underconstrained. Understanding dark energy to the percent level in the acceleration era and tens of percent in the high-redshift pre-acceleration era remains one of the long-term programmatic goals of cosmology. This also requires support for further methodological advances to reduce systematic uncertainties.

Multiple methods bring robustness. Characterizing dark energy and modified gravity through as many different methods as possible provides valuable cross-checks and data consistency tests as methods hit systematic floors. We see critical opportunities here both in tests of expansion history (e.g., the current tension in the value of H_0) and growth (e.g., the current concerns within lensing and cluster analysis regarding the value of σ_8).

Multiple observatories bring robustness. If there is evidence of deviations from General Relativity or evidence for dynamical dark energy, it is essential to cross-check results with independent experiments using multiple techniques with careful control of systematic errors.

Cross-correlations are ever more important. Applying similar methods over the same volume brings about numerous cross-correlations that have proven to be very valuable. In order to make maximal use of cross-correlations, it is essential to support simulation and data processing/analysis tools that are compatible across surveys and collaborations.

Blind analysis is desirable but challenging. This is especially true with upcoming complex analyses that involve numerous, often subjective, analysis choices. Executing a blind analyses requires careful methodological planning, extensive support from simulations, and delicate coordination, particularly when combining numerous methods across a broad collaboration.

Studies of dark energy and modified gravity are related. All but the simplest dark energy models predict modifications of gravity, although the two can be distinguished by comparing probes of the background expansion and the growth of structure [16]. Both exhibit deviations from ΛCDM on cosmological scales (e.g. [17, 27]) that can be tested with the same probes. They should be studied as one field.

Dark energy science in the 2030s will require technical R&D support. The path forward into the 2030s will require an ongoing investment at the observational frontier. Whether by mapping of huge cosmic volumes or by discovery and characterization of rare transients, improving our view of dark energy will require continued technological ambition. Design and development of a broad technical portfolio in this decade will be needed to achieve the necessary capabilities, both statistically and systematically, in a cost-effective manner.

The field of cosmology has been adept at unifying large teams to produce and optimize state-of-the-art facilities, the products of which have advanced many areas of astrophysics. We believe that the mystery of dark energy and the diverse range of measurements that bear on it remains a compelling driver to motivate this development in the coming decade.

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