Research Statement
Dynamical dark energy: theoretical constructions, constraints and connections to observations

Jolyon Bloomfield

Center for Radiophysics and Space Research,
Cornell University, Ithaca, NY 14853, USA

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I. Summary

Our best theory of gravity, general relativity, is currently under sharp scrutiny. In the ultraviolet, we expect modifications in order to accommodate a quantum description of gravity, while in the infrared, we have the cosmological constant problem. Motivated by these issues, my research focuses on understanding the predictions of modified gravity theories, and constraining the theory space through observations. My primary interest lies in understanding the cosmological evolution of dark energy and its effect on structure formation in our universe. In particular, what parameter space characterizes models of dark energy, what theoretical limits can we place on this parameter space, and how can we use observational evidence to apply further constraints to our understanding of dark energy?

II. Dark Energy

The past fifteen years have been a golden age for cosmology, with many experiments providing unprecedented insight into the foundations of the universe. The startling discovery that the expansion of the universe is accelerating [1, 2] has shaped our view of the cosmic inventory. It is now believed that only 5% of the universe is made out of known particles, while 25% is comprised of an unknown "dark matter", and 70% constitutes an even more mysterious "dark energy," which is responsible for the accelerated expansion. Observations of supernovae, gravitational lensing by galaxy clusters, and the distribution of galaxies and galaxy clusters within the universe all support the existence of this dark energy.

The most basic model of dark energy suggests that it is the vacuum energy of space, known as the cosmological constant. In order to agree with observations, the cosmological constant would need to be incredibly small. However, simple arguments suggest that it should be 120 orders of magnitude larger than the value we measure for it. This huge discrepancy indicates that our current understanding is incomplete. Through the combination of a variety of measurements, we hope to constrain the possibility that the accelerated expansion of the universe is caused by a dynamical field, rather than a cosmological constant. As more observational results become available, opening up the exciting possibility of new insights into the nature of dark energy, it will be important to have a broad and general framework in which to interpret the data.

III. Approach

Dark energy affects the longest wavelength modes in the universe. As a distinctly infrared phenomenon, its associated effects can be described at leading order using the methods of effective field theory (EFT). Following the foundation of Weinberg [3], and building upon the work of Park *et al.* [4], my collaborators and I have constructed a general class of theories to describe models of dark energy [5]. We have taken an EFT approach to describe models where the low-energy theory is well-described by general relativity coupled to a single scalar field. This restriction is not as strong as it may seem; in the low-energy limit, most models of dark energy behave like a scalar field coupled to gravity.

This formulation is useful for investigating the background evolution of dark energy, and has been used as a basis for applying constraints from observational data by collaborators Mueller *et al.* [6]. However, truly discriminating between different models of dark energy will require an understanding of its effect on the growth of structure in the early universe. Our formulation is capable of describing cosmological perturbations, but for analyzing perturbative behavior, there is a more powerful technique.

Instead of constructing a theory to describe the entire evolution of dark energy, a more specialized approach describing just the perturbative behavior about a given background cosmology allows for a more general analysis. This approach has been shown to be particularly useful for the investigation of inflation by Cheung *et al.* [7], and a basic analysis has been applied to quintessence by Creminelli *et al.* [8]. This approach works for dark energy because the ΛCDM background evolution can be assumed as a starting point. My collaborators and I have applied this formalism to general dark energy models [9, 10], with particular emphasis given to understanding the modifications to gravitational behavior, particularly with regards to the growth of structure. This approach has the benefit of being a particularly powerful and general description of dark energy perturbations, and goes beyond the regime of validity of our background approach.

IV. Research Plan

The overarching goal of my work is to either confirm the existence of dynamical dark energy, or to categorically rule it out, requiring the existence of a cosmological constant. This goal will require observational data from Stage IV Dark Energy experiments such as WFIRST, Euclid, LSST, BigBOSS, and PFS, and possibly beyond. Recent work by Amendola *et al.* [11] suggests that future observational data may be powerful enough to rule out the most general of scalar field theories, and I will be helping to develop the tools to do so.

In the near term, I plan to accomplish the following goals:

- Categorically understand the contribution of various dark energy models to operators in our EFT formalism. This includes our previous work on the background formalism, popular models, and the most general single-field dark energy model possible.
- Isolate observable quantities from our perturbative EFT theory to facilitate rapid and model-independent comparisons with observational data.
- Understand theoretical constraints on dark energy models within the EFT context.
- Develop a codebase and techniques for numerically modelling the cosmological growth of structure based on the EFT formalism we have constructed, given a dark energy model, and use this to constrain the parameter space of individual models from comparisons to observational data. This is based on work currently in progress with collaborators.

Mid-term goals that I wish to pursue include the following:

- Construct our perturbative formalism in the language of the Parameterized Post-Friedmannian framework, in order to connect with previous results and techniques.
- Systematically compare observational constraints on operators in the background and perturbative formalisms.
- Refine our codebase to include techniques to study the range of predictions of dark energy scenarios in a model-independent manner and compare with observational data, enabling us to place generic constraints on dark energy models.

In the long term, I hope to investigate the degree of accuracy and level of validity in non-linear regimes will our EFT formalism will need to achieve in order to constrain the most general of scalar field theories. Following this, I hope to construct a pipeline that will be able to take new observational data as it becomes available and combine it with previous information in order to rapidly construct model-independent constraints on dark energy. I hope that one day, we will be able to know whether or not dark energy is dynamical, or if we truly live in a universe with a cosmological constant.

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