Final Technical Report Cover Page

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1.0 Executive Summary

The search for evidence of new physics via its signatures in the cosmos is a cornerstone goal of the Office of High Energy Physics in the DOE Office of Science. Indeed, the current concordance cosmological model provides intriguing hints for beyond-the-standard-model (BSM) physics, such as dark matter and dark energy. Recently, a potential breakdown has appeared in this model, which could be initial evidence toward a further important revision in our fundamental theoretical understanding of cosmology. This breakdown is reflected in disagreements between inferences of the current expansion rate of the universe, H_0 (the Hubble constant), based on indirect, cosmological data (e.g., from the early universe) and based on direct, local measurements. Despite significant effort, a compelling new concordance cosmological model has yet to be found; achieving significant progress on this front was the first major focus of the project. Theoretical considerations indicate that if the observational discrepancies are not due to systematic errors, they strongly suggest new physics operating in the redshift range just prior to recombination, when cosmic microwave background (CMB) photons last scattered. Crucially, almost all such models produce unique signatures in the CMB temperature and polarization power spectra, which will be measured with unprecedented precision by ongoing and upcoming experiments, including the DOE-supported CMB-S4 project. However, these subtle hints of new physics must be uncovered from beneath a swath of Galactic and extragalactic foreground contamination. Current CMB analysis methods, although powerful, do not optimally infer the CMB power spectrum in the presence of non-Gaussian foregrounds. There is thus scope for theoretical improvement in this foundational challenge of cosmological inference, which formed the second major focus of the project.

The primary objectives of the project were two-fold: (1) to develop new theoretical models in cosmology that can restore concordance amongst the full suite of cosmological data sets, thereby potentially providing evidence of novel BSM physics; (2) to develop new theoretical machinery to enable significant sensitivity improvements in searches for new physics in cosmology, particularly via the CMB power spectrum. The two objectives are intertwined, as the analysis methodology improvements in (2) will enable the tightest possible constraints on the signatures of new physics predicted by the novel scenarios in (1). The theoretical approaches to restore concordance focused on models involving novel scalar field dynamics in the pre-recombination universe (the “early dark energy” scenario and modifications thereof), as well as couplings between this field and other components in the standard cosmological model, such as dark matter. We also studied a model featuring a generalization of the decaying dark matter scenario, in which a sub-component of dark matter converts into dark radiation at late times in cosmic history. While these ideas are mostly driven by phenomenological considerations, this tactic has proven extremely successful in cosmology throughout the past few decades, including in the early history of evidence for dark matter and dark energy. The new theoretical machinery envisioned in (2) is undergirded by developments in signal processing and machine learning, which will enable improvements in CMB power spectrum estimation in the presence of non-Gaussian foreground contaminants. In turn, this will yield optimal sensitivity in searches for new physics in the CMB, by maximizing the cosmological information that is extracted from this observable.

The most ambitious outcome of this work would be the construction of a new cosmological model that restores concordance amongst data sets. Although the individual models studied here did not fully achieve that goal, significant progress in narrowing down the model space was made, as described below. Moreover, the outcome of the methodological improvements in (2) will significantly impact a wide range of theoretical cosmology, by enabling the tightest possible constraints on any model that leaves novel signatures in the CMB temperature and polarization power spectra.

2.0 Background

In recent years, a discrepancy has emerged between inferences of the current cosmic expansion rate, H_0 (the Hubble constant), based on indirect, cosmological data (e.g., from the early universe) and based on direct, local measurements. The most precise indirect approach relies on using the physical size of the sound horizon in the primordial plasma as a "standard ruler", thus setting an absolute distance scale, while the most precise direct approach relies on the classical "distance ladder" built on parallaxes, Cepheid variable stars, and Type Ia supernovae. The former method can be applied to data from the CMB, or alternatively big bang nucleosynthesis (BBN) in combination with other constraints on the cosmic matter density, both yielding consistent results around $H_0 \sim$ 67-68 km/s/Mpc. The distance ladder approach yields higher values around $H_0 \sim$ 73-74 km/s/Mpc, a discrepancy that has now reached ~4 sigma significance. While some alternative local probes of H_0 have yielded somewhat lower values, it is generally true that the discrepancy has persisted across different choices of data sets.

If not due to systematic errors, this situation suggests a potential breakdown in the concordance cosmological model, which could be a sign of new fundamental physics, such as a new component in the cosmic energy budget or a new interaction in the dark sector. The most compelling solutions to the H_0 discrepancy thus far are based on modifications of the standard cosmic history in the epoch immediately preceding recombination, when CMB photons last scattered. Many of these modifications are designed to decrease the sound horizon, and thereby increase the inferred H_0, while leaving the fit to the CMB data intact. One such proposal is the "early dark energy" (EDE) scenario, which achieves the necessary phenomenology by introducing a (pseudo-)scalar field with an axion-like potential that is tuned to achieve the necessary phenomenology. To resolve the H_0 discrepancy, the EDE field is initially frozen due to Hubble friction in the early universe, thus acting as dark energy (i.e., a cosmological constant), which increases the expansion rate and hence decreases the sound horizon in the early universe. The EDE field then begins to roll down its potential when the Hubble parameter drops below the field's effective mass. The potential is designed such that the field's energy density then quickly redshifts away, faster than matter.

While this scenario can successfully reconcile the CMB and local-H_0 data, it runs into trouble when confronted with large-scale structure (LSS) data, as first shown by the PI. These problems arise primarily due to shifts in the standard cosmological parameters that are required to preserve the fit to the CMB, which lead to conflicts with weak lensing and galaxy clustering data. This conclusion was later extended to broad classes of EDE-like models. Intriguingly, however, the latest high-resolution CMB data from the Atacama Cosmology Telescope (ACT) mildly prefer the existence of EDE, as shown in recent work led by the PI. While the robustness of these hints to systematic effects in the ACT data remains to be confirmed, this result motivates further investigation of the EDE scenario, in particular the exploration of modifications that can preserve the model's success with H_0 while ameliorating its problems with LSS data. In addition, it is possible that mild tensions between ACT and Planck constraints on the EDE scenario could also be pointing toward the need for such modifications. In this project, we considered modifications to the EDE scenario motivated both by fundamental theory (string theory) and by phenomenological considerations. We explicitly constructed an alternative approach to the EDE scenario, which yielded similar observable predictions with far less fine-tuning (e.g., we were able to explain the apparent coincidence between the EDE epoch and the epoch of matter-radiation equality). We also studied a late-universe model with potential implications for H_0, featuring a generalization of the decaying dark matter scenario.

Fundamental physics discoveries in cosmology have relied heavily on studies of the CMB over the past few decades. The CMB provides us with an exquisite probe of the cosmos only 380,000 years after its birth; moreover, its statistical properties are sensitive to physical processes occurring over nearly the entire history of the universe. While the Planck satellite has extracted much of the information in the primary CMB temperature fluctuations, significantly more powerful constraints remain to be harvested from the primary polarization fluctuations and the secondary temperature fluctuations generated by effects in the late universe, particularly on small angular scales. Indeed, this is a major focus of the DOE-supported CMB-S4 project. Amongst the most important science goals of upcoming CMB analyses is a transformative improvement in constraints on the particle content of the early universe, in particular light relic particles (e.g., neutrinos) that may have been in thermal contact with the primordial plasma at early times, as quantified by the parameter N_{eff}, the effective number of relativistic species. Such particles leave an imprint in the small-scale CMB temperature and polarization power spectra. Furthermore, in addition to N_{eff}, most of the new-physics scenarios that have been suggested to resolve the H_0 discrepancy, including those considered in the proposed investigation, leave distinct signals in the CMB. These signatures may lie directly in the primary CMB power spectra, or be imprinted by late-time processes such as gravitational lensing.

In essentially all cases, optimal constraints on these novel cosmological scenarios require optimal CMB power spectrum inference, as this is presently the only cosmological probe that can simultaneously constrain all parameters in the cosmological model. However, the current standard approach used in CMB analyses does not fully extract all cosmological information. In particular, the standard method does not optimally account for the presence of non-Gaussian foreground contamination; instead, foregrounds are treated in a manner that is only optimal for Gaussian random fields. The standard approach is based on the measurement of auto- and cross-power spectra for a set of maps at a few observational frequencies, to which a model comprised of various foreground templates (and the primary CMB) is fit at the power spectrum level. In this project, we took the first steps toward developing new theoretical machinery to improve upon this widely used approach, while requiring minimal additional modeling complexity. The key insight is that optimal weighting of both noise and foreground contamination can be performed in the wavelet domain, a powerful framework developed in signal processing in recent decades. We took the first steps toward modeling the power spectrum of internal linear combination-cleaned CMB maps in the wavelet domain. Due to the limited timeframe of the project (8 months), the full scope of this effort will require follow-up work.

3.0 Project Objectives

The primary objectives of the project were two-fold: (1) to develop new theoretical models that can restore concordance amongst cosmological data sets, thereby potentially yielding evidence for new physics beyond the standard model; (2) to develop new theoretical machinery to enable significant sensitivity improvements in searches for new physics in cosmology, particularly via the CMB power spectrum. The two objectives are intertwined, as the analysis methodology improvements in (2) will enable the tightest possible constraints on the signatures of new physics predicted by the novel scenarios in (1). The theoretical approaches to restore concordance focused on novel scalar field dynamics in the pre-recombination universe, and potential couplings between this new field (or fields) and those already present in the standard cosmological model, e.g., dark matter. While this approach is driven by phenomenology, this tactic has proven extremely successful in cosmology throughout the past few decades, including in the early history of evidence for dark matter and dark energy. The new theoretical machinery envisioned in (2) is undergirded by developments in signal processing and machine learning, which will enable improvements in CMB power spectrum estimation in the presence of non-Gaussian foreground contaminants. In turn, this will yield optimal sensitivity in searches for new physics in the CMB, by maximizing the cosmological information that is extracted.

4.0 Description of Activities Performed

The first major thrust of the project developed new cosmological models. The aim of these scenarios was to explain the current puzzle in measurements of the Hubble constant (see above) with relatively minimal extensions to the standard cosmological model, while maintaining consistency with the full suite of current cosmological data. The overarching goals of this thrust was to construct new models, identify novel phenomenological signatures of these scenarios, and assess their consistency with data (including non-astrophysical constraints).

We built a new model via an extension to the EDE model described above. The EDE model invokes a new light (pseudo-)scalar field that briefly contributes substantially to the cosmic energy budget just prior to recombination, before rapidly fading away. During this period, the field slightly accelerates the background expansion, which reduces the physical size of the sound horizon at last scattering; this then leads to a higher inferred value of H_0 in fits to CMB data. However, this model exacerbates currently mild tensions between the amplitude of late-time density fluctuations inferred from CMB and LSS data. This occurs because of changes to the standard cosmological parameters needed to accommodate the EDE field in fits to CMB data, as the EDE slightly suppresses the growth of perturbations during the epoch in which it is dynamically important. Preserving the fit to CMB data requires increasing the DM density (ω_c) and the scalar spectral index (n_s). The net effect is an increased tension with LSS data, or, if one performs a joint analysis of CMB and LSS data in the EDE model, the data do not prefer the existence of this new component. In addition, the apparent coincidence between the onset of the EDE dynamics and the epoch of matter-radiation equality is unexplained.

This situation motivates the exploration of minor tweaks to the EDE scenario that could maintain its ability to yield "high" H_0 values from CMB data while not requiring increases in ω_c and n_s as compared to ΛCDM, and also provide a dynamical explanation for the coincidence between the EDE "critical redshift" (z_c) and z_{eq}. In this project, we built an "Early Dark Sector" (EDS) model with precisely these features. We considered a model featuring an EDE-dark matter (DM) coupling, in which a small change in the DM mass has a dramatic effect on the background evolution of the EDE scalar. In this regime, the DM can act as a trigger for the dynamical evolution of the EDE, such that the scalar is naturally released from Hubble friction near z_{eq}. The effective potential dictates the transition in the EDE evolution from frozen to rolling. The timing of this moment is approximately determined by the criterion $V_{eff}' \sim H^2\varphi$. If $|V_{eff}'| \gg |V_{eff}'|$ at this time, then the release and subsequent decay of the EDE can be considered to be "triggered" by the DM coupling, thus explaining why $z_c \sim z_{eq}$.

We imposed the following demands on this "trigger EDS" model for it to resolve the Hubble tension and explain the EDE coincidence problem:

1. Resolve the Hubble tension via EDE-like dynamics, with $f_{EDE} \sim 0.1$ and $z_c \sim 10^{3.5}$, and a release from Hubble friction $|d \ln \varphi / d \ln a| \sim |V_{eff}'/(\varphi H^2)| \sim 1$ just prior to this epoch. Here, $f_{EDE} \equiv \rho_{EDE}(z_c)/\rho_{tot}(z_c)$ is the maximal EDE contribution to the cosmic energy budget.

2. DM-triggered decay: the release from Hubble friction is triggered by the EDE-DM coupling rather than the bare potential $V(\varphi)$, i.e., $|V_{\mathrm{eff}}'| \gg |V'|$.
3. No fine-tuning of initial conditions: the mechanism of DM-induced release from Hubble friction at the critical redshift z_c is independent of the initial value of φ (thereby resolving another problem of EDE, namely, the fine-tuning of the initial field value).

These requirements significantly narrowed the possibilities for both $m_{DM}(\varphi)$ and $V(\varphi)$. The requirement that the EDE field is triggered by the DM for generic initial field values suggested the need for a coupling where $d\ln m_{DM}/d\varphi \propto \varphi$, with a sufficiently flat bare potential, unlike previous models, which focused largely on axion-like potentials. In addition, this form of coupling makes the fifth-force enhancement of DM growth vanish as $\varphi \to 0$ and thus removed the problematic enhancement of S_8 found in previous EDE models. Thus, our model simultaneously solved both the EDE coincidence problem and improved the S_8 problem of EDE.

A simple, theoretically well-motivated coupling satisfying these requirements is $m_{DM}(\varphi) = m_0(1+g\varphi^2/M_{pl}^2)$. The interaction with φ is naturally Planck-suppressed, and the coupling constant g is expected to be an $O(1)$ number based on standard effective field theory arguments. This coupling is consistent with the symmetries of the low-energy effective field theory (wherein φ is typically associated with a pseudo-scalar), and is also a natural expectation of string theory.

For the bare potential, the condition $V_{\mathrm{eff}}' \gg V'$ suggests a potential similar to those of axion monodromy models (without the periodic cosine term), which naturally feature flattened potentials at large field values: $V(\theta)=V_0\theta^n/(1+\theta^{np})^{1/p}$, where $\theta \equiv \varphi/f$. For simplicity we focused on positive integer values of n and p. This form of the potential manifests a plateau $V \to V_0$ at large field values ($\theta \gg 1$), a minimum $V \sim \theta^n$ at small field values ($\theta \sim 0$), and a transition region at $\theta \sim 1$, with the sharpness of the transition controlled by p.

As shown in our paper published in *Physical Review D* [1], this model satisfies all of the above criteria. It naturally resolves the EDE coincidence problem at the background level without any fine-tuning of the coupling to dark matter or of the initial conditions. When fitting to current cosmological data, including that from the local distance ladder, CMB, and LSS, our EDS maximum-likelihood model performs comparably to EDE for resolving the Hubble tension, yielding $H_0 = 71.2$ km/s/Mpc. However, fitting the *Planck* CMB data requires a specific range of initial field positions to balance the scalar field fluctuations that drive acoustic oscillations, providing testable differences with other EDE models and a platform for future model-building.

In addition to this "trigger EDS" model, in the project we also studied a different class of model with the potential to ameliorate the Hubble tension (and the "S_8 tension"), namely, a generalization of the well-studied decaying dark matter scenario. In this model, some fraction of the dark matter has converted into dark radiation since the release of the CMB. Such a scenario encompasses and generalizes the standard decaying dark matter model, allowing additional flexibility in the rate and time at which the dark matter converts into dark radiation. We constrained this scenario with a focus on exploring whether it could solve (or reduce) the Hubble and S_8 tensions. We found that such a model is effectively ruled out by CMB data, in particular by the reduced peak-smearing due to CMB lensing on the power spectrum and the excess integrated Sachs--Wolfe (ISW) signal caused by the additional dark energy density required to preserve flatness after dark matter conversion into dark radiation. Thus, such a model does not have the power to reduce cosmological parameter tensions without further modifications. Along the way, we also corrected errors in previous analyses of this model and publicly released our benchmarked, thoroughly validated Boltzmann code. Our conclusions extended and generalized related conclusions derived for the standard decaying dark matter model. Our paper describing this work was recently accepted for publication in *Physical Review D* [2].

The final paper completed during this project focused on developing a new approach to CMB data analysis, with the ultimate goal of improving the precision of cosmological parameters estimated from the CMB power spectrum. To achieve this, we have been developing a formalism to use foreground-cleaned maps built using needlet internal linear combination (NILC) methods to measure the CMB power spectrum. Such maps can more robustly clean foregrounds in the mm-wave sky than current methods that only operate at the power spectrum level, by adjusting NILC frequency map weights in both real and harmonic space. However, the major challenge in this approach is modeling residual foreground contamination in the NILC CMB map. We have developed a mathematical formalism based on a generalization of the MASTER algorithm, which is a widely used method for treating the effect of non-uniform pixel weighting (or masking) in CMB power spectrum analyses. The first step in our approach was to derive a generalization of MASTER (termed “reMASTERed") that can account for correlations between the field of interest and the weight (or mask) field, an effect that was neglected in the original MASTER paper.

Indeed, it is often the case that the map and mask in CMB analyses are correlated in some way, such as point source masks, which have nonzero correlation with CMB secondary anisotropy fields and other mm-wave sky signals. In such situations, the MASTER approach gives biased results, as it assumes that the unmasked map and mask have zero correlation. While such effects have been discussed before with regard to specific physical models, we derived a completely general formalism for any case where the map and mask are correlated. We showed that our result reconstructs ensemble-averaged angular power spectra to effectively exact precision, with significant improvements over traditional estimators for cases where the map and mask are correlated. An important consequence of our result is that for maps with correlated masks, it is no longer possible to invert a simple equation to obtain the true power spectrum from the observed (masked) power spectrum. Instead, our result necessitates the use of forward modeling from theory space into the observable domain of the masked power spectrum. We publicly released our software implementation of these results, which are applicable in wide range of settings. Our paper describing this work was published in *Physical Review D* [3].

5.0 Conclusions and References

In this project, we have developed new theoretical models with the potential to restore concordance amongst cosmological data sets, while also ruling out some scenarios that had previously shown promise in this regard. Our work sets the stage for further model-building and analysis to obtain robust evidence for beyond-standard-model physics in cosmology. We have also developed new theoretical machinery to enable significant sensitivity improvements in searches for new physics in cosmology, particularly via the CMB power spectrum, an effort which we are continuing in ongoing work.

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