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Light Relics of the Early Universe

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Abstract

The research supported by this award invested two types of signals left over of the early universe that might be observed in maps of the universe: (i) particles produced (thermal relics) during the hot big bang and (ii) signals left in the seeds of structure left from from an inflationary epoch prior to the hot big bang (inflationary relics). The research into thermal relics exposed new signatures of the cosmic neutrino background in the distribution of galaxies, culminating in the first measurement of the neutrino induced phase shift of the baryon acoustic oscillations. Subsequent research explored implications of constraints on hot light particles from the cosmic microwave background and the large scale structure for the physics of dark matter. Green and collaborations also investigated cosmological signatures from the inflationary epoch, including the best constraint to date on oscillatory features in seeds of structure and the first viable proposal to test the quantum origin of structure in the universe.

1 Introduction

The research supported by this proposal broadly invested signals of light particles in cosmological observables. The goal of this program was to explore how fundamental physics in the early universe manifests itself in cosmic microwave background and large scale structure data, and to develop strategies and analyses to unearth these signals. The research accomplishments can be organized into two main themes, *Theme 1* investigated signals of particles produced thermally during the radiation dominated era of the early universe, and *Theme 2* explored the impact of new particle and interactions during inflation on the statistical properties of the primordial density fluctuations.

The exploration of the universe during the radiation era (*Theme 1*) has a wide variety of implications for fundamental physics. There are a number of well motivated-reasons to believe the universe was once hot enough to for quarks to have been liberated (i.e. hotter than the temperature of the QCD phase transition). At these high temperatures, even extremely weak couplings between new particles, like axions, and the Standard Model would still bring these new particles into thermal equilibrium. Cosmic searches for these particles can find these relics or rule out these models. These new particles may also mediate forces with dark matter and gives us an additional handle on dark sectors and their interactions with the Standard Model. Finally, cosmic neutrinos are one relic of this kind that we expect even in a standard cosmic history. The unique signatures these neutrinos leave gives us a window into the early universe and the physics of the neutrino sector. The research accomplishments of this program include the measurement of cosmic neutrinos in large scale structure (LSS), new constraints on dark sectors from the cosmic microwave background (CMB) and LSS.

The inflationary epoch (*Theme 2*) is when the seeds of structure in the universe were created. It was widely believed that this occurred from quantum vacuum fluctuations that were stretched into large classical fluctuations by the exponential expansion that defines the inflationary era. This mechanism also allows any new particle lighter than the inflationary Hubble scale to be created from the vacuum and influence the formation of structure. As a result, this kind of ubiquitous particle production can leave a variety of additional signatures in the CMB and LSS. In addition, there are mechanisms for producing even more massive particles from the dynamics of the inflaton itself that are often distinguishable from the ordinary quantum fluctuations. The research accomplishments of this theme include the first viable proposal for distinguishing the quantum and classical origin of structure, an improved understand of quantum effects during inflation, new mechanisms for particle production during inflation, and a world leading constraint on related particle production mechanisms from a reanalysis of LSS data.

2 Accomplishments: Theme 1 – Light Thermal Relics

2.1 Neutrinos in Large Scale Structure

Neutrions were in equilibrium at temperatures $T \gg 1$ MeV and were produced in large numbers, comparable to the number of photons in the universe at that time. These relics neutrinos would have a temperature of 1.95 K today but have never been detected in the lab. In contrast, the cosmic signal of these neutrinos has been measured using the primordial abundances of elements,

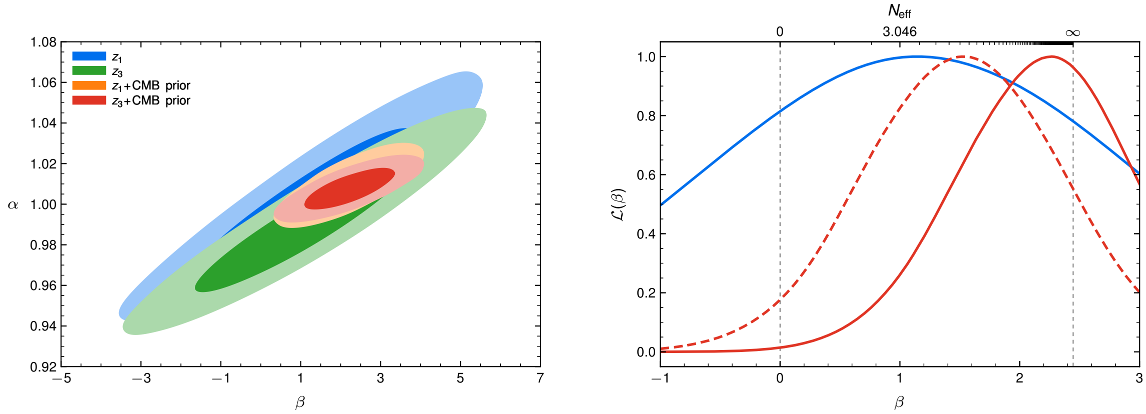

Figure 1: Measurement of $N_{\rm eff}$ using the phase shift of the BAO. Right plot shows the posterior distribution for β, the size of the phase shift, or equivalently of $N_{\rm eff}$. The left hand plot shows the degeneracy between β and α, the BAO frequency that is measures the expansion history.

and from the cosmic microwave background. Both measurements encode the energy density in a parameter called $N_{\rm eff}$ (the effective number of neutrino species), which in the Standard Model is given by $N_{\rm eff} \approx 3.044$. Additional measurements of $N_{\rm eff}$ probe the history of the universe after the time of neutrino decoupling and tests for the presence of additional light particles.

One of the major accomplishments of this research program was the development of LSS as a probe of $N_{\rm eff}$. In [1], Green and collaborators performed the first complete investigation of the signals of $N_{\rm eff}$ in the matter power spectrum and its observability in the next generation of cosmic surveys. One of the hallmark signals of cosmic neutrino is a phase shift in the location of the fourier space peaks in the baryon acoustic oscillations (BAO). This signal is unique to particles that travel faster than the speed of sound in the primordial plasma around the time or recombination. Neutrinos create this signal because they are relativistic and free-streaming at these temperatures. Green and Ridgway further explored the unique character of this signal in [2] where they developed a detailed semi-analytic understanding of the phase shift.

In [3], Green and collaborators used this phase shift to present the first measurement of $N_{\rm eff}$ in the distribution of galaxies. They analyzed the data from BOSS DR12, focusing solely on the BAO signal. Using the template for the phase shift calculated in [1], they shifted the locations of the peaks according to the $N_{\rm eff}$ template while marginalizing over the BAO frequency (which is the location of the peak in the two point correlation function in position space). This procedure was shown to produce an unbiased measurement of $N_{\rm eff}$ using forecasts and the Dark Patchy mock catalogue. Imposing the condition that the background expansion was consistent with a homogenous cosmology consistent with Planck, they found $N_{\rm eff} > 0$ at 99.5% confidence, as shown in Figure 1.

2.2 Dark Sectors

Cosmic neutrinos manifest themselves in cosmic observables through their gravitational influence. As a result, the same types of signatures that reveal the nature of the comic neutrino background can also be used to explore other kinds of dark sectors (i.e. new particles that whose influence is largely gravitational). The dark matter itself is one important example, as we have measured its presence in the CMB, both through its gravitational influence on the acoustic peaks at recombination and through the gravitational lensing of the CMB by dark matter at lower redshifts. This broad interplay between $N_{\rm eff}$ and dark matter research has been explored by Green in the context of several future CMB experiments and was summarized in [4].

In addition to the impact on $N_{\rm eff}$, specific models of dark matter may induce signatures on cosmic observables through non-gravitational effects. Dark matter annihilation has been one well known examples where the CMB has yield powerful constraints. However, as was shown by the PI, with Meerburg and Meyers, that future CMB observations will make very limited improvements in these measurements. The effect on the CMB is localized at low ℓ as the primary signal arises from additional scaling at lower redshifts. Green collaborators provided the first analytic model for the signal and explained these properties of the forecasts.

More optimistically, Green showed that direct interactions between the Standard Model and the dark matter can be well tested both with current and future measurements of the CMB. In work with de Putter, Dore, Gleyzes, and Meyers [2], Green showed that milli-charged dark matter is very strongly constrained by the CMB. Naively, for large enough dark, a dark milli-charged dark matter subcomponent would be degenerate with the baryon density. However, since milli-charged dark matter would appear to increase the baryon density without significantly changing the number of free electrons, it has a significant impact on the high-ℓ damping tail. The milli-charged dark matter effectively behaves like a change to the primordial helium abundance at the time of recombination. As a result, Green was able to show that the fraction of tightly coupled milli-charged dark matter is $< 0.6\%$ (95% confidence) given current observations. This constraint would improve to $< 0.1\%$ (95% confidence) with CMB-S4.

Green, in collaboration with Kaplan and Rajendran [5], also investigated models of dark matter coupled directly to neutrinos. Much like the case of the case of milli-charged dark matter, when the coupling is large, the dark matter acts as an effective increase to the mass of the neutrino. Neutrino mass is very tightly constrained by measurements of the lensing of the CMB and is currently constrained to be $\sum m_\nu < 120$ meV. Green reinterpreted this as a bound on the fraction of dark matter coupled to neutrinos and showed current observations limit this fraction to $< 0.45\%$ (95% confidence). This can reach $< 0.13\%$ (95% confidence) with the next generation of cosmic surveys. Constraints on the full parameter space are shown in Figure 2.

3 Accomplishments: Theme 2 – Inflationary Relics

3.1 Quantum Aspects of Inflation

The quantum nature of the fluctuations produced during inflation is one of the most compelling ideas in modern physics: the physics of the very small is responsible for creating the largest structures in the universe. One of the key accomplishments of the research in this theme was the development of a precise test of this idea. In work with Porto [6], Green showed that one cannot distinguish classical and quantum fluctuations from Gaussian statistics. However, in the presence of primordial non-Gaussianity, only quantum fluctuation can produce bispectra (fourier

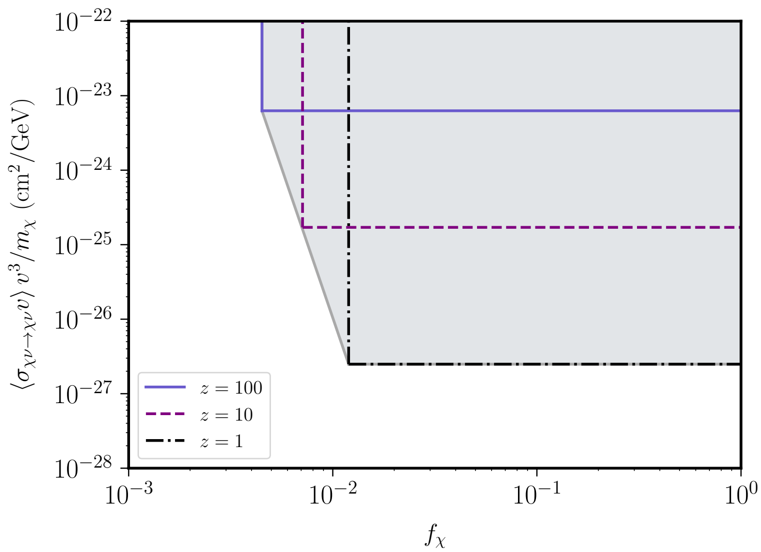

Figure 2: Constrain on the fraction of dark matter interacting with neutrinos, f_χ, with a cross-section $\sigma_{\chi\nu\to\chi\nu}$. The excluded region is sensitive to the redshift where the momentum exchange becomes efficient, which, in turn, depends on the cross-section.

transform of the three point function) with only a total energy pole, e.g.

$$\langle\zeta(\vec{k}_1)\zeta(\vec{k}_2)\zeta(\vec{k}_3)\rangle \propto \frac{1}{(k_1+k_2+k_3)^n} \tag{3.1}$$

where $|\vec{k}_i| = k_i$ and n is some positive integer that controls the order of the total energy pole. In contrast, classical fluctuations will always produce poles at physical momenta as well and cannot produce a total energy pole in isolation. These physical poles are measurable in a sufficiently sensitive test of primordial non-Gaussianity. This research is part of a longer term goal of the program to constraint the structure of non-Gaussian observables using locality and causality [7].

The understanding of quantum effects during inflation has a long history. Loop corrections to cosmological correlators are notoriously difficult to calculate and have led to much disagreement in the literature. A second major accomplishment of this research was the development of the Soft de Sitter Effective Theory by Cohen and Green [8]. This effective field theory has led to a dramatic simplification of the loop corrections in de Sitter space and inflationary cosmologies. It allows for several line proofs of the all orders conservation of the scalar (adiabatic) and tensor fluctuations during inflation, the latter being proven by Green and Cohen for the first time. In addition, it confirms and simplifies the result of anomalous dimension calculations previously shown by Green and Premkumar [9]. This framework was then used by Green, with Cohen, Premkumar and Ridgway [10], to calculate the next-to-next-to leading order corrections to stochastic inflation, including the first higher derivative term in the equation for the Markovian evolution.

3.2 Features from Inflation

The possibility that scale invariance is weakly or even strongly broken during inflation is well motivated from attempts to be robust models of inflation. Scale invariance is usually a consequence of a global shift symmetry which is typically broken in UV complete examples. Green

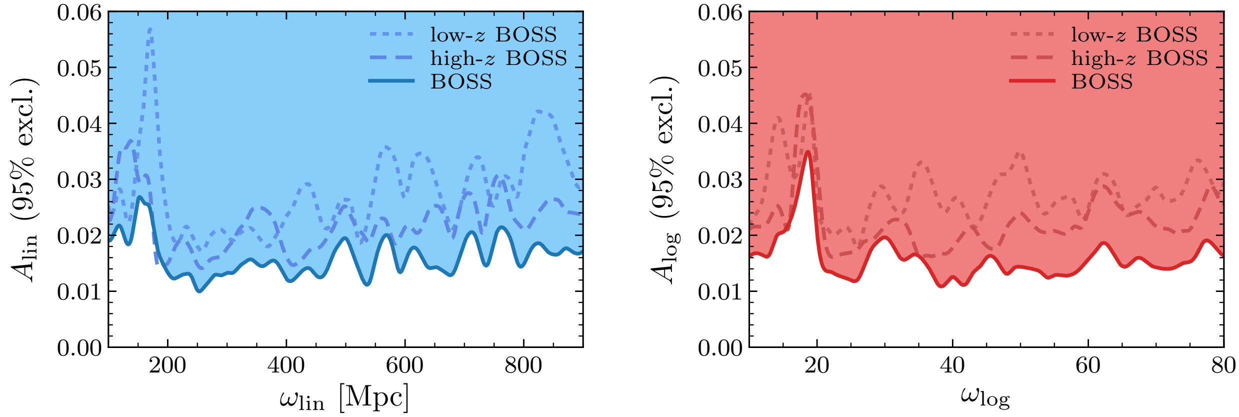

Figure 3: Constraints on primordial oscillations in the power spectrum using BOSS DR12 data and compared to constraints on the same models using the Planck satellite. The left (right) plot shows the constraint on the amplitude of oscillations linear (logarithmic) in the length of the wavenumber.

and collaborators investigated this possibility both from a model building perspective and from observations.

First, with Garcia Garcia and Amin [11] (see also [12]), Green investigated a new class of inflationary models where scale-invariance (the shift symmetry) is broken by random "impurities" in the inflationary potential. This model is a natural possibility in the effective theory of inflation, in direct analogy with the effective theory description of impurities in solids. In this analogy, particle production during inflation arises from the same physics that gives us Anderson localization in solids. An exponentially large number of particles are produced in a random fashion. The density fluctuations follow the same statistics as a log-normal random walk and produce a number of interesting observational signatures including scale dependent features in the power spectrum and primordial black holes.

While deviations from scale invariance are well motivated theoretically, they are strongly constrained observationally. One of the key accomplishments of this program was a new (world leading) observational constraint on this kinds of primordial features in collaboration with Beutler et al. Prior to this work, the best constraints on primordial features came from the CMB via the Planck satellite. However, what Green and collaborators realized is that these signals could be searched for in LSS without being limited by non-linear effects. This analysis was inspired by their previous success with the neutrino phase shift and the baryon acoustic oscillations (BAO) more generally. They developed the framework for this search analytically, showed it gave robust and unbiased results in simulations and then performed the analysis of BOSS DR12 data. In some cases, this analysis is similar to searching for a second BAO with a different frequency and amplitude. The results shown in Figure 3 improve upon Planck by a factor of 2-4. In addition, they showed that future LSS surveys will dramatically outpace the CMB in sensitivity, as seen in Figure 4.

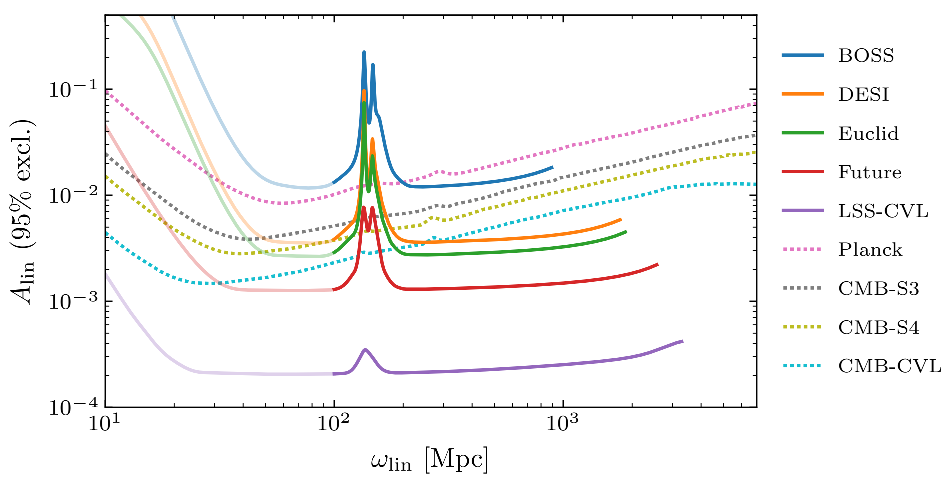

Figure 4: Forecasts for the measurement of the amplitude of linear oscillations in the matter power spectrum. Future LSS are capable of improving upon a cosmic variance limited CMB survey by an order of magnitude and nearly two orders of magnitude over Planck.

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