Cosmic Neutrinos and Other Light Relics

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Cosmological measurements of the radiation density in the early universe can be used as a sensitive probe of physics beyond the standard model. Observations of primordial light element abundances have long been used to place non-trivial constraints on models of new physics and to inform our understanding of the thermal history to the first few minutes of our present phase of expansion. Precision measurements of the angular power spectrum of the cosmic microwave background temperature and polarization will drastically improve our measurement of the cosmic radiation density over the next decade. These improved measurements will either uncover new physics or place much more stringent constraints on physics beyond the standard model, while pushing our understanding of the early universe to much earlier times.

1 Introduction

The primordial light element abundances and the angular power spectrum of the cosmic microwave background (CMB) are sensitive to the total radiation density that was present in the early universe, usually parametrized through a quantity $N_{\text{eff}}$. In the standard models of particle physics and cosmology, the value of $N_{\text{eff}}$ measures the total energy density of cosmic neutrinos. In more general models, however, $N_{\text{eff}}$ receives contributions from all forms of relativistic species apart from photons present in the early universe. This means that $N_{\text{eff}}$ can be used as a sensitive probe of physics beyond the standard model. The next generation of CMB experiments will drastically improve our constraints on $N_{\text{eff}}$, opening a characteristically new regime in the cosmological search for new physics.

The quantity $N_{\text{eff}}$ is typically defined as the ratio of the energy density of all dark radiation (that is all radiation except photons) to that of photons:

$$N_{\text{eff}} = \frac{8}{7} \left( \frac{11}{4} \right)^{4/3} \frac{\rho_X}{\rho_\gamma}.$$  

The standard model predicts $N_{\text{eff}} = 3.046$.

2 Observational Signatures

2.1 Primordial Light Element Abundances

The process by which light elements form in the early universe, known as big bang nucleosynthesis (BBN), is affected by the presence of dark radiation due to its impact on the expansion rate. For example, an increase in $N_{\text{eff}}$ tends to produce a higher helium-4 abundance. For higher radiation density, the expansion rate is higher, which implies that the temperature drops more quickly with time. This results in a higher neutron-to-proton freeze-out ratio and less time for...
free neutron decay. Thus, there remains a higher number density of neutrons surviving when the
universe cools sufficiently for the formation of helium nuclei, thereby producing more helium-4
than in the standard scenario\textsuperscript{1,3,4}.

Astrophysical measurements of the primordial helium-4 abundance have for a long time
provided the best constraint on $N_{\text{eff}}$, though recently improved measurements of the primordial
deuterium abundance have become competitive with those of helium-4\textsuperscript{5,4}. The current best
measurement of $N_{\text{eff}}$ from primordial abundances is\textsuperscript{4}

$$N_{\text{eff}}^{\text{BBN}} = 3.28 \pm 0.28,$$

which is fully consistent with the predictions of the standard model.

2.2 Cosmic Microwave Background

Dark radiation impacts the angular power spectrum of the CMB in a number of ways. The most
prominent observational signature is the effect of increased damping in the presence of higher
radiation density\textsuperscript{6}. Perturbations in free-streaming radiation (such as cosmic neutrinos) also
lead to shifts in the amplitude and phase of the acoustic peaks which approach constants at small
angular scales\textsuperscript{7,8}. The phase shift is of particular interest, since it is not degenerate with other
cosmological parameters and will become increasingly important in driving future constraints
on $N_{\text{eff}}$\textsuperscript{8}. Furthermore, since the phase shift is only sourced by free-streaming radiation, mea-
surements of the CMB can also be used to distinguish the nature of dark radiation\textsuperscript{9,10,11,8}.
The phase shift due to cosmic neutrinos has recently been isolated and detected in the Planck
temperature data\textsuperscript{12}.

Measurements from the Planck satellite using both temperature and polarization currently
provide the best constraint on $N_{\text{eff}}$, giving\textsuperscript{13}

$$N_{\text{eff}}^{\text{CMB}} = 3.04 \pm 0.18.$$  

We see that this measurement is consistent with the prediction of the standard model and also
with the measurements of primordial abundances.

Future measurements of the CMB, in particular from a ground-based CMB Stage-IV ex-
periment, are expected to improve on the current constraints on $N_{\text{eff}}$ by about an order of
magnitude\textsuperscript{14,15}. The phase shift of the acoustic peaks will play an increasingly important role
in these constraints\textsuperscript{8}. The $E$-mode polarization power spectrum has sharper acoustic peaks
than that of the temperature power spectrum, thus yielding a more accurate measurement of
the phase shift and $N_{\text{eff}}$. Since gravitational lensing of the CMB tends to smooth out acoustic
peaks, delensing which sharpens peaks can improve the constraints on $N_{\text{eff}}$\textsuperscript{8,16}.

2.3 Complementarity

Measurements of $N_{\text{eff}}$ from the CMB are now more precise than those from primordial abundance
observations, though these should be viewed as complementary rather than competing probes.
The two measurements are sensitive to different aspects of the radiation content of the universe
(since for example the primordial abundances depend weakly on the distribution function of
active neutrinos\textsuperscript{17}), and so combining these measurements provides a more comprehensive
picture than either alone. Furthermore, these two measurements are sensitive to the radiation
energy density at different times in the cosmic history, thereby allowing constraints on the
evolution of the radiation density and the thermal history of the universe\textsuperscript{18,19,20,21,22}.

The CMB is also directly sensitive to the primordial helium abundance through its effect on
the damping tail. Such constraints from CMB Stage-IV will be more precise and much less sen-
sitive to astrophysical systematics than the current best observations of primordial helium\textsuperscript{15,8}. 
3 Theoretical Targets

Precise measurements of $N_{\text{eff}}$ naturally place constraints on many extensions of standard model physics. This includes for example gravitational waves\textsuperscript{23,24,25}, dark photons\textsuperscript{26,27,28}, sterile neutrinos\textsuperscript{29,30,31}, and many more\textsuperscript{19,32}.

Perhaps one of the most compelling motivations for studying $N_{\text{eff}}$ is that all light thermal relics contribute to $N_{\text{eff}}$ at a level which is determined by the spin and decoupling temperature alone\textsuperscript{33,11}. The minimum contribution from a thermal relic which decoupled after the QCD phase transition is roughly $\Delta N_{\text{eff}} \sim 0.3$ which is the regime currently probed by the Planck observations. The measurements of CMB Stage-IV will be sensitive to light relics which decoupled at much earlier times and higher temperatures. Light thermal relics with essentially arbitrarily high decoupling temperature always\textsuperscript{a} produce $\Delta N_{\text{eff}} \geq 0.027$\textsuperscript{33,11}. A CMB experiment which reaches this level of sensitivity will therefore either detect new physics, or rule out the existence of new light thermal relics, a conclusion which would have extremely far reaching consequences for particle physics\textsuperscript{34}.

Measurements of $N_{\text{eff}}$ therefore allow the CMB to be used as a window onto particle physics at energies much higher than are accessible by other means. The next decade of CMB observations will thus be an extremely exciting period for cosmologists and particle physicists alike.

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