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Cosmological constraints on small scale perturbations from the cosmic microwave background

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This is a summary of Author's thesis.

Solving an evolution of cosmological photon fluid provides us rich information of the early universe, since its anisotropies on the present sky, namely the linear anisotropies in the cosmic microwave background (CMB) are directly related to the primordial quantum fluctuations of fields during inflation. On the other hand, the resolution is strongly restricted due to a fundamental limitation coming from dissipation of the fluctuations on small scales. Inflationary period must continue at least 60 e-holdings to solve the initial condition problems of the hot Big Bang universe; however, the visible scales from the usual CMB temperature anisotropy observations correspond to just 7 e-holdings. Therefore, the smaller scales remain obscure despite the previous successful observations. Throughout this thesis, we present methods for investigating such small scale primordial fluctuations in the early universe by analyzing not the CMB intensity anisotropy but the CMB intensity *spectrum and spectrum anisotropy*, which are at second or higher order in principle.

First of all, we provide a brief review of general relativistic Boltzmann equations for the photon temperature perturbations including the polarizations at first order. Then, numerical integrations are demonstrated and angular power spectra for the linear perturbations are obtained. We also review approximation methods for calculating transfer functions in the end of chapter 3.

Chapter 4 is devoted to present a new framework for getting second or higher order anisotropies, which have richer information of primordial perturbations in their non-trivial spectral dependences. The difficulty at second order is addressed at the beginning, and then we derive and solve the second order Boltzmann equations for momentum dependent temperature perturbations explicitly and give a unified view to the anisotropic spectral distortions and the second order temperature perturbations. This method may be extendable to larger class of non-linear physics, and has a potential to give a general prescription to non-equilibrium physics. As an example, we apply it to the cubic order collision terms of the Compton scattering and show how to construct the solutions. Then, we find the linear y distortion and the higher order one, which are obtained as solutions to the cubic order Boltzmann equations in addition to the temperature perturbations. It also implies that there exist the cross correlation function between the temperature perturbations and y distortion without primordial non-Gaussianity in contrast to the previous estimations.

Current constraints on the spectral distortions are obtained as $\mu < 9 \times 10^5$ (95%C.L.) and $y < 1.5 \times 10^5$ (95%C.L.) by COBE/FIRAS, which can be recast into $\mathcal{P}_\zeta(k) < O(10^{-5})$ in $0.1 < k\mathrm{Mpc} < 10^3$ for the scale invariant case. The next observational projects, such as PIXIE will improve the constraints by 3 orders of magnitude, and the distortions from primordial curvature perturbations on small scales would be detectable [1]. In consideration of these prospects, we investigate the primordial gravitational waves, neutrino isocurvature perturbations and primordial non-Gaussianity on small scales by using the spectral μ distortion and its cross correlations with the temperature anisotropies in chapter 5. To be more specific, the constraints on the amplitudes and tilts of the primordial gravitational waves and the Gaussian squared Neutrino isocurvature density modes are derived. Suppose the blue tilted gravitational waves power spectrum on the small scales; $\{n_T, r\} = \{1, 0.1\}$, we show that they may be detectable; otherwise such scenarios which produce the significant primordial gravitational waves on small scales can be excluded. In addition, Joint analyses with the polarization E modes are demonstrated for giving the upper bound on non-Gaussianity based on experiment like PIXIE. Chapter 6 is devoted to another possibility for investigating the small scale physics, namely, acoustic reheating. We point out that there exist anisotropies in the acoustic reheating as in the case with the spectral distortions if we assume primordial non-Gaussianity on small scales. We calculated the temperature auto correlation function including the second order reheating effects. The anisotropic acoustic reheating should be subdominant compared to our observed CMB temperature auto correlation functions so that we obtained the constraints on the non-linear parameters. These constraints are relatively weak, but it is unique window for highly squeezed non-Gaussianity since significant contribution is possible once we have a large squeezed non-Gaussianity even at the beginning of the universe.

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[1] μ is a chemical potential.