論文の内容の要旨

Cosmological constraints on short-wavelength primordial perturbations
（短波長原始ゆらぎに対する宇宙論的制限）

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Primordial perturbations of a huge range of wavelengths are generated quantum mechanically in the early universe (see e.g. [1–4]). Those of largest wavelengths are observed as anisotropy of the cosmic microwave background (CMB, see e.g. [5–7]), or they provide the seeds of the large-scale structures of the universe we see today. The nature of primordial perturbations on large wavelengths has been well determined (see [8] in 2015 for the latest results obtained by the Planck collaboration), while that of primordial perturbations of shorter wavelengths is less understood. Though simplest models of inflation predict almost scale-invariant power spectrum (see e.g. [1–4, 9–11]), different models of the early universe predict different properties of short-wavelength perturbations, for instance, larger power on small scales (see e.g. [12] and references therein), and so investigation of primordial power on small scales can provide helpful information about the early universe.

Primordial perturbations of shorter wavelength cause a wealth of phenomenology, through which their properties can be constrained. For instance, if some region strongly deviates from other places in the universe, that region collapses to a black hole (called a primordial black hole, PBH) [13–15]. That is, black holes could have been generated even in the early universe, well before structures such as stars are formed. So far there is no conclusive observational evidence for substantial formation of such black holes in the past (see [12] for a holistic summary of observational upper bounds on PBHs), which fact itself provides valuable information about the nature of primordial perturbations (see e.g. [16, 17]), and hence about mechanisms of generation of primordial perturbations.

Another example of phenomenology related to primordial perturbations of short wavelengths is dissipation of them due to diffusion processes, and this diffusion leads to energy release into the universe, which was originally stored in sound waves (see one of the earliest works [18]). This energy release causes the slight increase in the global temperature of the universe, or deviations of the energy spectrum of photons in the universe from a Planck spectrum (called CMB distortions), depending on when the dissipation happens, namely, depending on comoving scales of perturbations.

If primordial power on small scales is larger than the prediction of the almost scale-invariant fluctuations, compact dark matter (hereafter abbreviated as DM) halos may be formed in the early universe ($z \sim 1000$). Annihilation of DM may be highly efficient in these mini-halos, and hence they may be detected on earth. In other words, observations of gamma-rays or neutrinos can be used to constrain these mini-halos, which can then be translated into constraints on primordial power on small scales (see [19] for a discussion about constraints on primordial power obtained by gamma-rays from these mini-halos).

In this dissertation, investigation of primordial perturbations of short wavelengths is discussed through these kinds of phenomenology. This dissertation is organized as follows.

Chapter 2 is dedicated to brief reviews of relevant topics; PBHs, CMB spectral distortion and compact DM mini-halos are reviewed.

Supermassive black holes (SMBHs) of $10^9 \sim 10^{10} M_\odot$ have been observed at high redshifts, and there has been no established explanation about how such gigantic black holes could have been formed by such early times. In Chapter 3, the possibility of PBHs as the seeds of these SMBHs observed at high redshifts is discussed. If primordial perturbations follow a Gaussian distribution or one similar to it, PBHs larger than $10^4 \sim 10^5 M_\odot$ are excluded due to constraints on CMB spectral distortion. This is because in order for the probability of PBH formation being sufficiently large to explain SMBHs, the amplitude of primordial perturbations of wavelengths corresponding to the scales of the seeds of SMBHs has to be very large, which causes CMB spectral distortion to a level that is inconsistent with observational upper bounds on CMB spectral distortion obtained by COBE/FIRAS. We discuss models which predict highly non-Gaussian perturbations to evade CMB distortion constraints, and in these models PBHs can be produced whose mass is as large as necessary to account for the observed SMBHs at high redshifts and whose abundance is also adjustable to match observations. This Chapter is based on a work in preparation [20] and a part of [21].

In Chapter 4, acoustic reheating is discussed, which is a slight increase in the global temperature of the universe, resulting from dissipation of primordial perturbations after Big Bang nucleosynthesis (BBN). This acoustic reheating causes a slight decrease in the baryon-to-photon ratio η. The values of η at BBN and the photon decoupling have been independently determined from observations of the abundance of the light elements in the universe and CMB anisotropy, which means if η decreases too much, it contradicts with these observations. From this consideration, upper bounds on primordial perturbations are obtained which dissipate after BBN but before the moment after which dissipation of perturbations causes CMB spectral distortion, noting perturbations of wavelengths which cause substantial CMB distortion have already been tightly constrained. This Chapter is based on [22].

Cosmological perturbations can be decomposed into scalar, vector, and tensor components, and Chapters 2-4 are devoted to discussions of investigation of short-wavelength primordial *scalar* perturbations. In Chapter 5, investigation of primordial short-wavelength *tensor* perturbations is discussed. It is known that scalar, vector and tensor perturbations evolve independently in linear theory, but they are coupled at the second-order level. For instance, scalar perturbations are generated from second-order tensor perturbations. If the amplitude of these induced scalar perturbations is sufficiently large (order unity), these perturbations collapse to form PBHs. Since there has been no conclusive evidence for the existence of PBHs, overproduction of PBHs is forbidden to be consistent with observations. This consideration leads to upper bounds on induced scalar perturbations, which can be translated into upper bounds on the amplitude of primordial *tensor* perturbations on small scales. This Chapter is based on [23] and a work in preparation [24].

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