学位論文要旨

Dark Energy with Large-scale Inhomogeneities
（大規模非一様性を持つダークエネルギー）

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The standard cosmological model (ΛCDM model) is very successful in explaining different observations such as the cosmic microwave background (CMB), the statistics of perturbations to CMB, the accelerating late-time expansion, and the formation of the large-scale structure (LSS) in matter distribution. The ΛCDM model generally bases on several assumptions, within which is the cosmological principle assuming homogeneity and isotropy of the universe on large scales. Nevertheless, there are anomalies in large-scale observations, such as the low multipole anomalies in CMB, indicating possible modifications to the cosmological principle.

In this thesis, model formulations for dark energy with large-scale inhomogeneities are presented based on ultralight-mass scalar fields as an attempt to illuminate the nature of dark energy associated with these anomalies. The large-scale inhomogeneous dark energy slightly breaks the cosmological principle, hence has the potential to account for part of the forementioned anomalies. The ultralight scalar fields that are responsible for the dark energy in the models also relate the interests of this study to the axion-like particles (ALPs) predicted in the string landscape.

First, as a heuristic example for inhomogeneous dark energy, a dark energy model with nearly “frozen” dynamics is presented. This is a specific model associated with a particular open inflationary scenario. Initially motivated by previous research, in this scenario, our universe is considered as an open universe created in the bubble nucleation associated with open inflation. A slow-roll inflationary phase followed the Coleman-De Luccia quantum tunnelling from the ancestor false vacuum of inflaton Ψ, driving it to the true vacuum we live in today. A canonical ultralight scalar field ϕ minimally coupled with the inflaton Ψ via metric can be considered a free field on the tunneling background, possibly leaving residual effects on the present observable universe. These are superhorizon modes that fluctuate on scales far beyond the curvature scale and evolve most slowly in time, named supercurvature modes. The frozen expectation value of the supercurvature modes of ϕ observed within the present horizon can be interpreted as the dark energy density observed by handling its fluctuations stochastically. This model can be named the supercurvature-mode dark energy (ScmDE) model.

However, the scope of application and prediction ability is restricted by the random field handling for ScmDE. On the other hand, ScmDE requires specific initial conditions associated with a particular inflationary scenario. Hence, as a generalization to the ScmDE model, a general dynamical dark energy model with large-scale inhomogeneities sourced by a dynamical scalar field is presented. By handling the inhomogeneities introduced by dark energy as cosmological perturbations on superhorizon scales in a flat universe, the equations governing the evolution of these perturbations together with the background are derived. The formulation focuses on the late-time evolution, where predictions for the expansion rate and the dark energy equation of state (EoS) can be obtained under different model parameters.

The large-scale inhomogeneities of the dark energy could induce possible observable imprints, such as contributions to the CMB anisotropies through the late-time integrated Sachs-Wolfe (ISW) effect. Using the observational data of CMB, constraints on the amplitudes of the fluctuations or perturbations related to model parameters are obtained and discussed. Further, as another example of the model application, possible corrections to the measurements of luminosity distance with light propagation with inhomogeneous dark energy is estimated utilizing the obtained constraints. Although the order of the corrections seems not big enough to account for the observed anisotropies in luminosity distances, various model parameters remain to be explored, and initial conditions associated with the ultralight scalar fields before the matter-dominant epoch are also interesting.

As a short summary, dark energy models with large-scale inhomogeneities are formulated and evaluated quantitatively in this thesis. Base on the formulation, possible observable imprints that could arise from the inhomogeneous model are investigated. The models predict unique characteristic imprints on observations from the inhomogeneous dark energy sourced from dynamics of an ultralight scalar field, which has the potential to be constrained or falsified by on-going and future projects focusing on dark energy, such as DES, DESI, Euclid, WFIRST, LSST-DESC, etc., together with increasing understandings of the systematics in cosmological observations.