論文の内容の要旨

Dark matter search with high-energy gamma-ray observations

(高エネルギーガンマ線による暗黒物質探査)

氏 名　廣島　渚

We can access dark matter of mass $m_{\rm DM} \gtrsim \mathcal{O}(1)$ TeV by measuring high-energy emissions from the Universe. Weakly Interacting Massive Particle (WIMP) is one of the strongest candidates for dark matter which achieves the relic density by the freeze-out mechanism. The canonical cross-section of the annihilation into the standard model particles is $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm$^3/s$. For WIMP of $m_{\rm DM} \sim \mathcal{O}(1-100)$ GeV, γ-ray observations of dwarf spheroidal galaxies (dSphs) have constrained the annihilation cross-section to be smaller than the canonical value. WIMP of mass $m_{\rm DM} \gtrsim \mathcal{O}(1)$ TeV are less explored. In this thesis, we discuss the feasibility of detecting heavier WIMP of $m_{\rm DM} \gtrsim \mathcal{O}(1)$ TeV in dSphs with Cherenkov Telescope Array (CTA). Compared to the current facilities, CTA can detect $\sim$ 10 times fainter γ-ray signals for $E_\gamma \gtrsim \mathcal{O}(1)$ TeV. The designed angular resolution reaches $\Delta\theta \lesssim 0.04$ degrees and dSphs are well-resolved as extended sources.

First, we evaluate how the detectability depends on the dark matter distribution in dSphs. The density profiles of dark matter in dSphs are actively debated topics and determined by observing stellar motions. The J-factor, which is a squared dark matter density integrated over the line-of-sight, can differ by orders-of-magnitude between profile models for example. The importance of the density profile increases for dark matter searches in dSph using CTA. We investigate how the spatial extension of dSphs affect the sensitivity to dark matter annihilation signals. For this purpose, we simulate a 500-hour observation of Draco dSph with CTA and perform likelihood analyses assuming 16 different profiles derived for Draco. We show that the accessible region of the annihilation cross-section differs by a factor of ~ 10 depending on the profiles. Both the J-factor and the spatial extension are responsible for the difference. We perform further analyses removing the dependence on the J-factor and prove that the spatial extension itself affects sensitivity. We introduce a new quantity θ_{90} to be a 90% confinement radius of the J-factor which parametrizes the compactness of the halo profile. When θ_{90} is larger than ~ 1 degree, we obtain a several times milder constraint on the annihilation cross-section compared to the case analyzing a point source of the same J-factor. In the most conservative case, CTA can detect the annihilation signals corresponding to the cross-section $\langle\sigma v\rangle \lesssim 10^{-22}$ cm$^3/s$ for dark matter of $m_{\rm DM} \gtrsim \mathcal{O}(1)$ TeV, which cannot be probed with other facilities. Some of the well-motivated models expecting resonant annihilations can be tested by observing dSphs with CTA. A wider parameter space can be explored if we observe dSphs of smaller spatial extensions and higher J-factors.

Second, we examine the uncertainty in the subhalo boost for dSphs. WIMP scenarios expect the existence of small scale halos beyond the resolution of the N-body simulations or observations. When such small halos in larger ones lie on our lines-of-sight, dark matter annihilation signals are boosted. Boost factors in the previous works differ by more than one order-of-magnitude because one has had to extrapolate N-body results in limited mass and redshift ranges to much wider. We reduce the uncertainties in the boost factor by developing a new analytical formalism to calculate the evolution of the subhalo. We characterize the mass-loss rate of the subhalos with the tidal-stripping at the first orbit after their accretion onto the hosts assuming the NFW profile for both the host and subhalos. In this way, we can cover more than 20 orders-of-magnitudes in the halo mass range and the redshift up to ~ 10. Our analytical results for the tidal mass-loss rate show good agreements with those obtained in N-body simulations. We derive the dependence of the mass-loss rate on the host mass and redshift. Combining the derived relation with the mass accretion history of subhalos in extended Press-Schechter formalisms, we obtain the mass function, the mass fraction, and the boost factor. The mass function and the mass fraction of subhalos are consistent with the results of N-body calculations in resolved regimes. The boost factor is less than ~ 1 for dSph scale halos while it can be as large as $\sim \mathcal{O}(10)$ for halos of the galaxy cluster scale. The uncertainty from the subhalo boost is negligible for dark matter search in dSphs.

CTA enhances our accessibility to the heavier WIMP of $m_{\rm DM} \gtrsim \mathcal{O}(1)$ TeV. When we search dark matter annihilation signals in dSphs using CTA, precise understandings about their density profiles are the most important ingredients to derive the dark matter properties. In addition to the known dependence on the J-factor, the spatial extension of dSphs affects the sensitivity. Contributions from the subhalos are negligible for the search in dSphs. We can access the unexplored parameter spaces even with the most conservative assumption about the dSph's density profiles. This does not depend on the boost factor. We conclude from these works that dSphs are well-motivated targets for CTA to search dark matter annihilation signals of which uncertainty coming from the subhalo boost is smaller than the other proposed targets for CTA.