Phenomenology of thermally produced hot and cold dark relics in naturalness-motivated extensions of the Standard Model

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Abstract

In the thesis, we investigate the phenomenology of two classes of models motivated by the naturalness criterion that feature thermal production of dark relics: astrophobic axion models and supersymmetric Twin Higgs models.

We first analyse the production of astrophobic axions which avoid astrophysical bounds by suppressing couplings to electrons and nucleons without increasing the axion decay constant. Since astrophobic axions have suppressed coupling to pions, they are primarily produced in lepton-flavour violating decays and lepton scatterings, however non-negligible contribution from kaon scatterings is generically also present. Depending on the axion mass, the population of axions acts as dark radiation or warm dark matter, which we take into account by exploiting mass-dependent bound on axions energy density parametrized by the additional effective number of neutrinos, $\Delta N_{\rm eff}$. We demonstrate that in astrophobic axion models with 2 Higgs doublets, the cosmological bound reads $f_a \gtrsim 8 \times 10^6$ GeV, and is weaker or comparable to the astrophysical constraint on axion-muon and axion-photon couplings, depending on specific couplings of the model. We show that the predicted sensitivities of future CMB experiments will significantly improve the cosmological bound probing up to $f_a \simeq 10^8$ GeV. Furthermore, we discuss how the generalization of the model to include three Higgs doublets allows for additional suppression of mentioned couplings, further relaxing astrophysical bounds and allowing for eV-scale axion mass. We categorize 3HDM astrophobic axion models based on their suppressed couplings and analyse their phenomenologies. Most astrophobic models are within the reach of Simons Observatory or the CMB-S4, and/or within the reach of IAXO or even BabyIAXO. In the naturally astrophobic model, axions are produced solely via non-perturbative effects which remain challenging to calculate exactly. Our estimate for cosmological bound can be as strong as $f_a \gtrsim 5 \times 10^6$ GeV for vanishing strange quark coupling, which potentially allows for explaining baryon asymmetry via axiogenesis and providing a non-relativistic population of axions playing the role of the DM produced via kinetic misalignment mechanism.

Next, we study two dark matter candidates produced via freeze-out in SUSY TH models: the twin stau and the twin bino. The former particle is charged under twin electromagnetism mediated by the massless photon. We found that mostly right-handed twin stau with mass between 400 and 500 GeV is a viable DM candidate, satisfying direct detection, collider, astrophysical, and cosmological constraints. We discuss the collider signatures of twin stau DM scenario and prospects of probing the scenario with future direct detection experiments, highlighting that LZ will probe most natural regions of the parameter space, corresponding to fine-tuning better than few percent. We demonstrate that twin bino-dominated neutralino is also valid DM candidate and show that overproduction can be relaxed by introducing $\mathbb{Z}_2$ symmetry breaking in the Yukawa sector, which does not spoil the solution to the hierarchy problem while alleviating the dark radiation problem. Similarly to twin stau DM, this scenario will best be probed by direct detection experiments. The LZ experiment will explore the most natural regions of the parameter space, corresponding to fine-tuning better than 10%.

In the thesis, we demonstrate that cosmological observations provide powerful constraints on models featuring thermal production of dark relics, probing energy scales inaccessible to ground-based experiments. By combining astrophysical, laboratory, and cosmological observations, we perform a complete analysis of the models, highlighting the intricate interplay between particle physics models and cosmology.