ABSTRACT

The primary focus of the thesis is on particulate thermal dark matter (DM) and their phenomenological implications in light of direct detection, indirect detection, and cosmological observations. The standard paradigm, Weakly Interacting Massive Particles (WIMP) is increasingly in tension by the null results of different terrestrial experiments. Broadly we have explored two possible alternatives of WIMP. Firstly, we have investigated the possible variants of $2 \rightarrow 2$ annihilation processes by introducing multipartite features in the dark sector while in the other part we have discussed generalization of $2 \rightarrow 2$ thermal freeze out mechanism to a multi-body $n \rightarrow 2$ annihilation framework. Within the $2 \rightarrow 2$ framework we augmented minimal Higgs portal DM model by both enlarging the stabilizing symmetry from Z2 to Z3 and incorporating multipartite features in the dark sector. We have demonstrated that in these non-minimal models the interplay of annihilation, co-annihilation, and semi-annihilation processes considerably relax constraints from present and proposed direct detection experiments while simultaneously saturating observed dark matter relic density. In particular we have explored the resonant semi-annihilation channel within the multipartite Z3 framework which results in new unexplored regions of parameter space that would be difficult to constrain by direct detection experiments in the near future.

In a related work we introduce a novel mechanism where processes that preserve number densities of the dark sector particles set the relic density of a thermal particulate DM. In a relatively degenerate multipartite dark sector if there is a considerable time lapse between the freeze out of various species then process like exchange between dark sector constituents can play the pivotal role of driving freeze out and setting dark matter relic density. We show that this unique mechanism can produce a viable GeV scale thermal dark matter. As a proof of principle we present simple scalar dark matter models to demonstrate this phenomenon.

The possibilities we have discussed so far typically produce viable GeV scale cold dark matter, which fits well within the ΛCDM framework. However, a growing conundrum in the mismatch between observations and simulations at the galactic scale structure of the universe provides a motivation for sub-GeV light dark matter (LDM) with self-interaction. An $n(\geq 3) \rightarrow 2$ process driving thermal freeze-out, can naturally lead to LDM. In this context we propose a novel example of this class of models called assisted annihilation where along with a pair of DM particles there are standard model(SM)-like assister in the initial state facilitating the annihilation of LDM. We show that depending on the mass hierarchy between the assister and dark matter there can be either a suppression or a boost of the effective cross section. This augmentation enables the possibility of O(100) MeV scale dark matter with perturbative coupling that saturates the relic density estimates while being relatively insulated from cosmological constraints like BBN and CMB. The constraint from the fixed target experiments for a light photophilic assisters has also been discussed.

From the point of view of model building the challenge is to have the flux suppressed $3 \rightarrow 2$ channel dominate over possible $2 \rightarrow 2$ processes. We explore the possibility of a resonant $3 \rightarrow 2$ assisted annihilation dominantly driving the freezeout of dark matter. We demonstrate that in a simple multipartite scalar extension of the Standard Model this can be realized in certain regions of parameter space to provide viable dark matter relic density, in agreement with observation. We demonstrate that for photophilic assisters parts of the parameter space are already constrained by indirect detection experiments and the measurements of CMB anisotropies while substantial regions remain beyond the present limit.