Snowmass2021 - Letter of Interest

Indirect Detection Aspects of Hidden Sector Dark Matter

Thematic Areas:

■ (CF1) Dark Matter: Particle Like
■ (CF3) Dark Matter: Cosmic Probes
■ (TF8) Theory Frontier: BSM model building
■ (TF9) Theory Frontier: Astro-Particle Physics and Cosmology
■ (TF11) Theory of neutrino physics
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model

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Abstract: Dark matter that is part of a hidden sector is one of the most widely studied paradigms in contemporary particle physics. This framework, vast in scope, is full of rich possibilities both theoretically and experimentally. Exploring and organizing such possibilities will be a critical part of the Snowmass 2021 process. This letter outlines some such avenues (with a particular emphasis on indirect detection, which is the most promising observational aspect of such setups), which can be part of various Snowmass studies of hidden sector dark matter.

Motivation Hidden sector dark matter (DM) is one of the most active fields of research at present. This class of models is broadly understood to encompass scenarios where dark matter does not share the symmetries of the Standard Model (SM) sector but resides instead in a hidden/dark/secluded sector that contains structure (symmetries, particles, and forces) of its own and interacts with the SM via heavy (portal) mediators. Because of the weakness of these portal interactions, either because the couplings are small or the mediators are heavy, hidden sector dark matter is generally characterized by small direct detection and production cross sections, but may feature large indirect detection signals, since dark matter annihilation can occur completely within the hidden sector with large cross sections. This broad framework for hidden sector dark matter can be realized in a vast number of ways, as evident from the plethora of hidden sector dark matter models present in the literature. The guiding principle for reasonable models generally constitutes of a combination of a reasonable production mechanism (such as WIMP freezeout) with some particle physics motivation for new physics (such as the hierarchy problem, generation of neutrino masses, the baryon asymmetry of the Universe etc). In these more specific frameworks, it is possible to obtain sharper predictions for indirect detection signatures signatures, establishing valuable links between theory and observation. A detailed exploration of the various theoretical and experimental possibilities for hidden sector dark matter – following the "leaving no stone unturned" philosophy – will be a crucial component of the Snowmass process. This letter is devoted to a cursory discussion of a handful of ideas that could be part of such an endeavor.

Hidden Sector WIMPs: The WIMP "miracle", our primary guiding principle in dark matter studies for several decades, continues to find use in hidden sector dark matter models. However, an important question that generally goes unanswered is why a secluded sector that is unaware of the SM content should know about the weak scale, which appears to be special to the SM. In seeking to answer this question, one can draw on various theoretical ideas - for instance, there are compelling reasons to believe that the underlying theory of nature should be supersymmetric, and it is known that gravity mediates supersymmetry breaking to all sectors with the same strength, so that even secluded sectors tend to be at the same mass scale. The realization of hidden sector DM in such a gravity mediated supersymmetric setup[1] generally features particles and their superpartners around the same mass scale, predicting indirect detection signatures featuring multi-step cascade decays quite different from vanilla hidden WIMP DM signals. For example, a typical dark matter annihilation process might be hidden sector dark matter fermion DM $\rightarrow$ hidden sector gauginos $\rightarrow$ visible sector gauginos+SM gauge/Higgs boson, with the gauginos further undergoing 3-body decay into SM fermions if R-parity is broken, as would be likely to accomodate baryogenesis into the framework[2]. In this manner, a single DM annihilation process could feature 3 or 4 cascade decay steps, giving 10 or more SM particles. The indirect detection signals of such processes at e.g. Fermi or CTA would be very different from those expected from simplified models of hidden sector DM, and it becomes important to consider such possibilities.

SIMPs and neutral naturalness: A recent alternative to WIMP paradigm is the strongly interacting massive particle (SIMP) paradigm, where the DM relic density is set by $3 \rightarrow 2$ self-annihilation processes with strong scale couplings and masses $\sim 0.1 - 1$ GeV. A natural hidden sector framework to realize the SIMP is neutral naturalness, motivated as a solution to the hierarchy problem, which posits the existence of a QCD-like twin sector where the twin mesons are ideal SIMP DM candidates. SIMP studies generally consider the DM to be protected by a symmetry and therefore absolutely stable. However, in a twin setup with three light hidden quark flavors, one of the twin mesons is in fact necessarily unstable, and small mixing with DM can also cause DM to be unstable and decay in observationally interesting ways[3]. In such frameworks, the prediction for SIMP DM decay signatures are generally quite sharp: DM tends to decay into

4 SM leptons (electrons or muons), giving indirect detection signals that are within the ranges of instruments such as COMPTEL, Voyager-1, and AMEGO.

FIMPs: Neutrino Portal Dark Matter: Feebly interacting massive particles (FIMPs) constitute another class of hidden sector dark matter, where the coupling between the hidden and SM sectors is so feeble that dark matter never thermalizes with the SM bath. FIMPs find a natural instantiation in neutrino portal models: these models are motivated by the BSM requirement for neutrino mass generation and feature right handed neutrinos, which are generically heavy and feebly interacting. Such models, with heavy right handed neutrino portals, can feature light (below the weak scale) dark matter candidates if hidden sector fermions coupling to the portal neutrinos themselves undergo a seesaw mechanism[4;5], or they feature additional structure, such as a light pseudo-Goldstone boson[6]. Such models are generally characterized by neutrino-rich final states for indirect detection. Due to the presence of light "sterile neutrinos", electroweak radiation associated with DM annihilating to SM neutrino final states can be conspicuously absent in such models[4]. Even more bizarre and exotic indirect detection signals are possible: for instance, in some scenarios, loop processes mediated by the heavy portal neutrinos can dominate over tree level processes, giving rise to identical DM decay widths into neutrinos, charged leptons, and SM gauge/Higgs boson final states, as well as a monochromatic neutrino line for arbitrarily high dark matter mass[7]. Such features are unlikely to be realized in any model with only tree level decays, highlighting the importance of careful consideration of such exotic frameworks.

Extremely (Astrophysically) Long-lived Mediators: While hidden sector particles can have lifetimes that are several orders of magnitude longer than those of SM particles, these lifetimes are still considered prompt for the purposes of indirect detection. Nevertheless, it is also possible that dark matter annihilates (or decays) into particles whose lifetimes are so long that they travel astrophysical distances before decaying, creating displaced vertices even for the purposes of indirect detection experiments. Such displaced decays can create exotic signals at dark matter detectors that are qualitatively very different from standard dark matter signals[8]. In particular, for Atmospheric Cherenkov Telescopes (ACTs) observing spatially confined dark matter sources (such as a dwarf galaxy) in wobble mode, while such extended signals can contaminate the control/background/OFF region, they also create several fascinating effects: the gamma-ray spectrum varies across the field of view of the instrument, featuring an increasingly suppressed flux at the highest energies at larger angles away from the centre of the dark matter source, creating novel observational challenges as well as opportunities.

References

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