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Publication Date

2009-09-15

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WIMPless Dark Matter

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Abstract. We describe the scenario of WIMPless dark matter. In this scenario of gauge-mediated supersymmetry breaking, a dark matter candidate in the hidden sector is found to naturally have approximately the right relic density to explain astronomical dark matter observations, but with a wide range of possible masses.

Keywords: dark matter, supersymmetry

PACS: 95.35.+d, 04.65.+e, 12.60.Jv

INTRODUCTION

New gauge symmetries are ubiquitous features of physics beyond the Standard Model, appearing in grand unified theories, many models of supersymmetry (SUSY) breaking, and string theory. But the appearance of any new symmetry can potentially have an impact on dark matter. If any of the new symmetries survive at low energies (perhaps even as a discrete symmetry), then the lightest charged particle will be stable and will contribute to the non-baryonic matter density observed by astronomical observation. If the relic density of the stable particle is close to the observed dark matter density, then the model provides a dark matter candidate as an additional feature.

We consider WIMPless models [1], a new class of models in which standard gauge-mediated SUSY-breaking (GMSB) models are extended by the addition of a hidden gauge sector. Since the hidden sector is generic, the soft SUSY-breaking scale induced by GMSB in this sector can be very different from the electroweak scale. But we will find that if a hidden particle at the hidden sector's soft mass scale is stabilized by a remnant symmetry, then this particle will have approximately the right relic density to be dark matter, regardless of what its mass happens to be. Remarkably, the relic density for this candidate matches that observed for dark matter for largely the same reason that WIMPs have the right relic density; indeed, we will argue that this "WIMPless miracle" is really a generalization of the WIMP miracle beyond the electroweak scale.

SETUP

The setup we consider is a simple extension of the standard setup for GMSB [2, 3]. Typically, the GMSB setup consists of a minimal supersymmetric Standard Model (MSSM) sector, as well as a sector in which supersymmetry is broken. The effects of SUSY-breaking are then mediated to the MSSM sector via messengers which are gauge-coupled to the MSSM. Integrating out these messengers generates a new scale

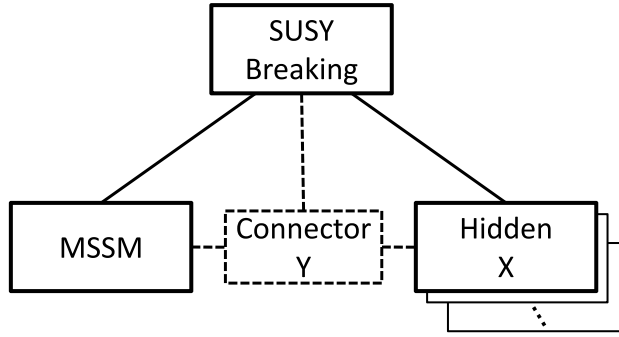


FIGURE 1. Sectors of the model. SUSY breaking is mediated by gauge interactions to the MSSM and the hidden sector(s), which contains the dark matter particle X . An optional connector sector contains fields charged under both MSSM and hidden sector gauge groups, which induce signals in direct and indirect searches and at colliders.

in the effective field theory of the MSSM sector, the soft scalar mass m_{soft} . Once the messengers and other heavy matter are integrated out, the MSSM is chiral and m_{soft} is the next energy scale; all matter either sits at this scale (e.g., Higgs bosons, W , Z , and neutralinos), or is much lighter (e.g., the photon and gluon).

All we add to this setup is one or more hidden sectors that are qualitatively similar to the MSSM sector. We only mean that these hidden sectors are supersymmetric gauge theories that receive the effects of SUSY-breaking from the same SUSY-breaking sector via GMSB (see Fig. 1); the gauge theory, and in particular the soft mass scale, can be very different from the MSSM. In the hidden sector, once we integrate out the heavy matter, we again find that the soft mass scale is the next energy scale, and all matter either sits at this scale (whatever it may be), or is much lighter. Finally, we assume that some symmetry stabilizes a particle with mass at the hidden sector soft mass scale.

RELIC DENSITY

In GMSB, the soft scalar mass scale is generated by a two-loop diagram, where messengers run in the loop. This scale is given by

$$m_{\text{soft}} \sim \frac{g^2}{16\pi^2} \frac{F}{M_{\text{mess}}}, \quad (1)$$

where g is the relevant gauge coupling, F is the vacuum expectation value of the SUSY-breaking F -term, and M_{mess} is the mass of the messengers. In particular, one expects that F/M_{mess} is determined by the dynamics of the SUSY-breaking sector, where the F -term is generated and where some gauge symmetries are broken, yielding a mass scale for the messengers. A specific example would be the case where messengers M_i , \tilde{M}_i gain mass through the SUSY-breaking sector Yukawa coupling. Assuming symmetries that prevent bilinear M_i, \tilde{M}_i couplings for the lightest messengers, the superpotential is

$$W = \sum_{i=\text{MSSM,hidden}} \lambda_i \Phi M_i \tilde{M}_i. \quad (2)$$

When SUSY breaks, the Φ field gets vacuum expectation value $\langle\Phi\rangle = M_{\text{mess}} + \theta^2 F$, and the soft mass scale in any sector is proportional to the same quantity, F/M_{mess} .

We thus find that

$$\frac{g_h^4}{m_h^2} \sim \frac{g_{EW}^4}{m_{EW}^2} \propto \frac{M_{\text{mess}}^2}{F^2} \approx \text{const} , \quad (3)$$

where g_h and m_h are the hidden sector gauge coupling and soft mass scale, respectively. This is important, as the ratio g^4/m_{soft}^2 sets the annihilation cross-section σ_{ann} through gauge interactions for a stable particle at the soft mass scale. (Models where the dark matter mass is determined by loop corrections were also studied in [4].) Moreover, if dark matter is thermal in the early universe, the relic density is largely determined by $\langle\sigma_{\text{ann}}v\rangle^{-1}$ [5].

This leads to an interesting result that is the crux of WIMPless dark matter: although the hidden sector soft mass scale could be anything, the relic density of a stable particle at the soft scale is essentially a universal constant, set by the physics of the SUSY-breaking sector via the ratio M_{mess}/F . But one can determine this ratio from the MSSM, and what the WIMP miracle really shows is that this universal relic density is approximately correct to explain the astronomical observations. We are thus left with a good dark matter candidate which gets the relic density right for the same reasons as the WIMP miracle, but for the much larger mass range $10\text{MeV} < M_{DM} < 10\text{TeV}$, where the lower bound is set by the requirement that the dark matter be non-relativistic at decoupling, and the upper bound is set by requiring perturbativity and unitarity [6].

Indeed, we see that, from this point of view, the lack of a good dark matter candidate in the MSSM sector is something of an accident. Without assuming R -parity conservation, the two massive stable particles of the MSSM are the electron and the LSP. Although the electron gets its mass from electroweak symmetry and thus might be expected to have mass at the electroweak symmetry breaking scale (close to the soft mass scale), in fact it is much lighter due to its extraordinarily small Yukawa coupling. This is basically a result of flavor physics, which we do not understand. And in GMSB, the LSP is the gravitino, which is not gauge-charged and does not sit at the soft scalar mass scale. Because of these two accidents, in GMSB, the MSSM does not have a stable particle at the soft mass scale. Provided a hidden sector does not have such accidents, it can provide a good dark matter candidate at the hidden soft SUSY-breaking scale.

HIDDEN SECTOR SYMMETRIES

Thus far, we have not discussed the nature of the symmetry which stabilizes the hidden sector dark matter particle. This symmetry could be a gauge, global or discrete symmetry. Discrete symmetries can naturally arise from the breaking of gauge symmetries; for example, if a field in the symmetric representation of a $U(N)$ gauge group gets a vacuum expectation value, a Z_2 subgroup of the diagonal $U(1)$ will survive.

We can then classify the continuous symmetries that are unbroken at the scale where the messengers are integrated out (so the mass of the gauge boson is much lighter than the messenger mass). The difference between a ‘‘gauge’’ and ‘‘global’’ symmetry, for our purpose, is the strength of the gauge coupling of the stabilizing symmetry (g_s) with

respect to the dominant gauge coupling g_h of the group under which the messengers are charged (which could, of course, be the same symmetry). We can think of the dark matter as being stabilized by an unbroken “global” symmetry if $g_s \ll g_h$ (the symmetry is truly global if $g_s = 0$). If $g_s \sim g_h$ then we think of it as stabilized by an unbroken gauge symmetry.

The cosmological history depends in detail on whether the stabilizing symmetry is gauged or global, because a gauged stabilizing symmetry implies that dark matter interacts largely through “dark radiation.” This case is discussed in detail in [7].

DETECTION

We have not discussed the detection possibilities for this scenario; they are discussed in detail in [8], with a focus on Yukawa couplings between dark matter and Standard Model particles via connector particles charged under both the Standard Model and the hidden sector. Interestingly, since this model naturally includes multiple hidden sectors that can each have a dark matter candidate, it includes the possibility of multi-component dark matter, with candidates at widely differing mass but with each composing a sizable, $\mathcal{O}(1)$ fraction of the relic density. Such a scenario provides the possibility of explaining several different experimental hints of dark matter as discussed, for example, in [9].

ACKNOWLEDGMENTS

We are grateful to the organizers of SUSY09, and thank J. Learned, L. Strigari, and X. Tata for discussions and collaboration. The work of JLF was supported in part by NSF grant PHY-0653656.

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