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Dark-Matter Particles without Weak-Scale Masses or Weak Interactions

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We propose that dark matter is composed of particles that naturally have the correct thermal relic density, but have neither weak-scale masses nor weak interactions. These models emerge naturally from gauge-mediated supersymmetry breaking, where they elegantly solve the dark-matter problem. The framework accommodates single or multiple component dark matter, dark-matter masses from 10 MeV to 10 TeV, and interaction strengths from gravitational to strong. These candidates enhance many direct and indirect signals relative to weakly interacting massive particles and have qualitatively new implications for dark-matter searches and cosmological implications for colliders.

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Introduction.—Cosmological observations require dark matter that cannot be composed of any of the known particles. At the same time, attempts to understand the weak force also invariably require new states. These typically include weakly interacting massive particles (WIMPs) with masses around the weak scale $m_{\rm weak} \sim$ 100 GeV–1 TeV and weak interactions with coupling $g_{\rm weak} \simeq 0.65$. An appealing possibility is that one of the particles motivated by particle physics simultaneously satisfies the needs of cosmology. This idea is motivated by a striking quantitative fact, the "WIMP miracle": WIMPs are naturally produced as thermal relics of the big bang with the densities required for dark matter. This WIMP miracle drives most dark-matter searches.

We show here, however, that the WIMP miracle does not necessarily imply the existence of WIMPs. More precisely, we present well-motivated particle physics models in which particles naturally have the desired thermal relic density, but have neither weak-scale masses nor weak force interactions. In these models, dark matter may interact very weakly or it may couple more strongly to known particles. The latter possibility implies that prospects for some dark-matter experiments may be greatly enhanced relative to WIMPs, with search implications that differ radically from those of WIMPs.

Quite generally, a particle's thermal relic density is [1]

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}, \tag{1}$$

where $\langle \sigma v \rangle$ is its thermally averaged annihilation cross section, m_X and g_X are the characteristic mass scale and coupling entering this cross section, and the last step follows from dimensional analysis. In the models discussed here, m_X will be the dark-matter particle's mass. The WIMP miracle is the statement that, for $(m_X, g_X) \sim (m_{\rm weak}, g_{\rm weak})$, the relic density is typically within an order of magnitude of the observed value, $\Omega_X \approx 0.24$. Equation (1) makes clear, however, that the thermal relic density fixes only one combination of the dark matter's mass and coupling, and other values of (m_X, g_X) can also give the correct Ω_X. Here, however, we further show that simple models with low-energy supersymmetry (SUSY) predict exactly the combinations of (m_X, g_X) that give the correct Ω_X. In these models, m_X is a free parameter. For $m_X \neq m_{\rm weak}$, these models do not include WIMPs but for all m_X they contain dark matter with the desired thermal relic density.

Models.—We will consider SUSY models with gauge-mediated SUSY breaking (GMSB) [2,3]. These models have several sectors, as shown in Fig. 1. The MSSM sector includes the fields of the minimal supersymmetric standard model. The SUSY-breaking sector includes the fields that break SUSY dynamically and mediate this breaking to the MSSM through gauge interactions. There are also one or more additional sectors which have SUSY breaking gauge-mediated to them; these sectors contain the dark-matter particles. These sectors may not be very well-hidden, depending on the presence of connector sectors (discussed below), but we will follow precedent and refer to them as

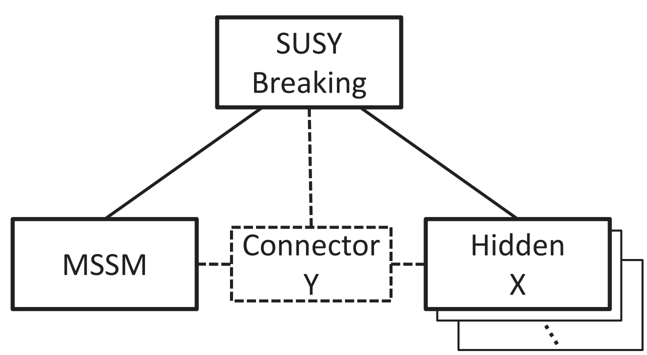

FIG. 1. Sectors of the model. SUSY breaking is mediated by gauge interactions to the MSSM and the hidden sector, which contains the dark-matter particle X. An optional connector sector contains fields Y, charged under both MSSM and hidden sector gauge groups, which induce signals in direct and indirect searches and at colliders. There may also be other hidden sectors, leading to multicomponent dark matter.

"hidden" sectors. For other recent studies of hidden dark matter, see Refs. [4].

This is a well-motivated scenario for new physics. GMSB models feature many of the virtues of SUSY, while elegantly solving the flavor problems that generically plague proposals for new weak-scale physics. Additionally, in SUSY models that arise from string theory, hidden sectors are ubiquitous. As a concrete example, we extend the canonical GMSB models of Ref. [3] to include one hidden sector. SUSY breaking gives vacuum expectation values to a chiral field S, with $\langle S \rangle = M + \theta^2 F$. We couple S to MSSM messenger fields Φ, $\bar{\Phi}$ and hidden sector messenger fields Φ_X, $\bar{\Phi}_X$ through the superpotential $W = \lambda \bar{\Phi} S \Phi + \lambda_X \bar{\Phi}_X S \Phi_X$. These couplings generate messenger F-terms $F_m = \lambda F$ and $F_{mX} = \lambda_X F$ and induce SUSY-breaking masses in the MSSM and hidden sectors at the messenger mass scales $M_m = \lambda M$ and $M_{mX} = \lambda_X M$, respectively.

Relic density.—Neglecting subleading effects and $\mathcal{O}(1)$ factors, the MSSM superpartner masses are

$$m \sim \frac{g^2}{16\pi^2} \frac{F_m}{M_m} = \frac{g^2}{16\pi^2} \frac{F}{M}, \tag{2}$$

where g is the largest relevant gauge coupling. Since m also determines the electroweak symmetry breaking scale, $m \sim m_{\text{weak}}$. The hidden sector superpartner masses are

$$m_X \sim \frac{g_X^2}{16\pi^2} \frac{F_{mX}}{M_{mX}} = \frac{g_X^2}{16\pi^2} \frac{F}{M}. \tag{3}$$

As a result,

$$\frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M}; \tag{4}$$

that is, m_X/g_X^2 is determined solely by the SUSY-breaking sector. As this is exactly the combination of parameters that determines the thermal relic density of Eq. (1), the hidden sector automatically includes a dark-matter candidate that has the desired thermal relic density, irrespective of its mass. (In this example, the superpartner masses are independent of λ and λ_X; this will not hold generally. However, given typical couplings $\lambda \sim \lambda_X \sim \mathcal{O}(1)$, one expects the messenger F-terms and masses to be approximately the same as those appearing in $\langle S \rangle$, and Eq. (4) remains valid.)

This analysis assumes that these thermal relics are stable. Of course, this is not the case in the MSSM sector, where thermal relics decay to gravitinos. This is a major drawback for GMSB, especially because its classic dark-matter candidate, the thermal gravitino [5], is now too hot to be compatible with standard cosmology [6]. Solutions to the dark-matter problem in GMSB include messenger sneutrinos [7], late entropy production [8], decaying singlets [9], and gravitino production in late decays [10], but all of these bring complications, and only the last one makes use of the WIMP miracle.

But the problem exists in the MSSM only because of an accident: the stable particles of the MSSM (p, e, ν, γ, $\tilde{G}$) have masses which are not at the scale m_{weak}. For the proton and electron, this accident results from extremely suppressed Yukawa couplings which are unexplained. There is no reason for the hidden sector to suffer from this malady. Generally, since m_X is the only mass scale in the hidden sector, we expect all hidden particles to have mass $\sim m_X$ or be essentially massless, if enforced by a symmetry. We assume that the thermal relic has mass around m_X, and that discrete or continuous symmetries stabilize this particle. The particles that are essentially massless at freeze-out provide the thermal bath required for the validity of Eq. (1). An example of a viable hidden sector is one with MSSM-like particle content (with possible additional discrete symmetries), but with different gauge couplings and with all Yukawa couplings $\mathcal{O}(1)$. The light particles are then the neutrinos, gluon, photon (and gravitino), while the remaining particles are all at the scale m_X. The lightest such particle charged under a (possibly discrete) unbroken symmetry will then be stable by hidden sector charge conservation.

One might worry that the extra light particles will have undesirable cosmological consequences. In particular, the number of light particles are constrained by big bang nucleosynthesis (BBN) [11] and (less stringently) the cosmic microwave background [12] even if they have no SM interactions. These constraints have been analyzed in detail in Ref. [13]. They are found to require $g_*^h (T_{\text{BBN}}^h / T_{\text{BBN}})^4 \leq 2.52$ (95% CL), where g_*^h is the number of relativistic degrees of freedom in the hidden sector at BBN, and T_{BBN}^h and T_{BBN} are the temperatures of the hidden and observable sectors at BBN, respectively. This bound may therefore be satisfied if, for example, $g_*^h < 2.5$ or if the hidden sector is as big as the MSSM with $g_*^h = 10.75$ but is slightly colder, with $T_{\text{BBN}}^h / T_{\text{BBN}} < 0.7$. Such discrepancies in temperature are possible if the observable and hidden sectors reheat to different temperatures [14,15] and need not alter the relic density calculation significantly [13].

To summarize so far: GMSB models with hidden sectors provide dark-matter candidates that are not WIMPs but nevertheless naturally have the correct thermal relic density. These candidates have masses and gauge couplings satisfying $m_X/g_X^2 \sim m_{\text{weak}}/g_{\text{weak}}^2$, and

$$10^{-3} \lesssim g_X \lesssim 3, \qquad 10 \text{ MeV} \lesssim m_X \lesssim 10 \text{ TeV}, \tag{5}$$

where the upper limits from perturbativity nearly saturate the unitarity bound [16], and the lower limits are rough estimates from requiring the thermal relic to be nonrelativistic at freeze-out so that Eq. (1) is valid.

Detection.—If the hidden sector is not directly coupled to the SM, then the corresponding dark-matter candidate interacts with the known particles extremely weakly. A more exciting possibility is that dark-matter interactions are enhanced by connector sectors containing particles Y

that are charged under both MSSM and the hidden sector, as shown in Fig. 1.

Y superpartner masses receive contributions from both MSSM and hidden sector gauge groups, and so we expect $m_Y \sim \max(m_{\rm weak}, m_X)$. Connectors interact through λXYf, where λ is a Yukawa coupling and f is a SM particle. X remains stable, as long as $m_X < m_Y + m_f$, but these interactions mediate new annihilation processes $X\bar{X} \to f\bar{f}$, $Y\bar{Y}$ and scattering processes $Xf \to Xf$. The new annihilation channels do not affect the thermal relic density estimates given above, provided $\lambda \lesssim g_{\rm weak}$.

Connector particles create many new possibilities for dark-matter detection. For example, in WIMPless models, the dark matter may have $m_X \ll m_{\rm weak}$. This motivates direct searches probing masses far below those typically expected for WIMPs. Because the number density must compensate for the low mass, indirect detection signals are enhanced by $m_{\rm weak}^2/m_X^2$ over WIMP signals.

To quantify this, we consider a simple connector sector with chiral fermions Y_{f_L} and Y_{f_R} and interactions

$$\mathcal{L} = \lambda_f X\bar{Y}_{f_L} f_L + \lambda_f X\bar{Y}_{f_R} f_R + m_{Y_f}\bar{Y}_{f_L}Y_{f_R}, \qquad (6)$$

where the fermions f_L and f_R are SM SU(2) doublets and singlets, respectively. The Y_f particles get mass from SM electroweak symmetry breaking. For simplicity, we couple Y to one SM particle f at a time, but, one Y can have multiple couplings or there can be many Y fields.

We begin with direct detection, and assume the interactions of Eq. (6) with $f = u$. These mediate spin-independent X-nucleus scattering through $Xu_{L,R} \to Y_{L,R} \to Xu_{L,R}$ with cross section

$$\sigma_{\rm SI} = \frac{\lambda_u^4}{2\pi}\frac{m_N^2}{(m_N + m_X)^2}\frac{[ZB_u^p + (A - Z)B_u^n]^2}{(m_X - m_Y)^2}, \qquad (7)$$

where A (Z) is the atomic mass (number) of nucleus N, $B_u^p = \langle p|\bar{u}u|p\rangle \simeq 5.1$, and $B_u^n = \langle n|\bar{u}u|n\rangle \simeq 4.3$ [17].

In Fig. 2, we present X-proton scattering cross sections as functions of m_X for various λ_u and $m_{Y_u} = 400$ GeV. Y_u receives mass from SM electroweak symmetry breaking, and this mass is well within bounds from perturbativity and experimental constraints [18]. Note that the cross sections are much larger than for neutralinos and many standard WIMPs, such as B^1 Kaluza-Klein dark matter [19]. Also, the framework accommodates dark matter at the GeV or TeV scale, which may resolve current anomalies, such as the apparent conflict between DAMA Collaboration experiment and other experiments [20].

We now turn to indirect detection and consider the interactions of Eq. (6) with $f = \tau$. These interactions can produce excess photon fluxes from the galactic center. The integrated flux is [21]

$$\Phi_\gamma = \frac{5.6 \times 10^{-10}}{\rm cm^2\, s} N_\gamma \frac{\sigma_{\rm SM} v}{\rm pb}\left[\frac{100\ {\rm GeV}}{m_X}\right]^2 \bar{J}\Delta\Omega, \qquad (8)$$

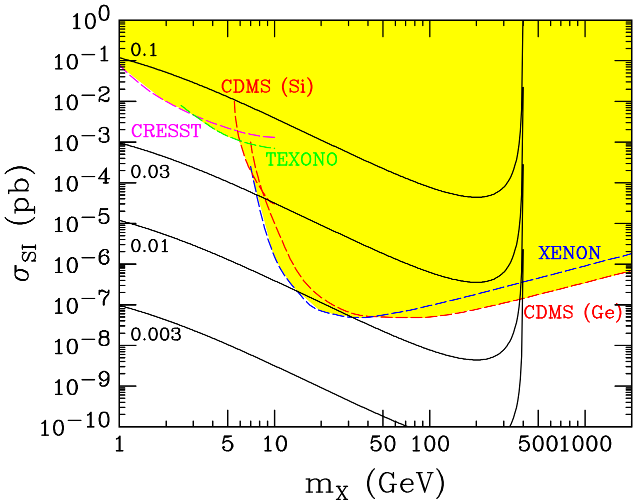

FIG. 2 (color online). Direct detection cross sections for spin-independent X-proton scattering as a function of dark-matter mass m_X. The solid curves are the predictions for dark matter without WIMPs with connector mass $m_{Y_u} = 400$ GeV and the Yukawa couplings λ_u indicated. The shaded region is excluded by CRESST [23], CDMS (Si) [24], TEXONO [25], XENON [26], and CDMS (Ge) [27].

where the cross section for $X\bar{X} \to \tau^+\tau^-$ is

$$\sigma_{\rm SM} v = \frac{\lambda_\tau^4}{4\pi}\frac{m_Y^2}{(m_X^2 + m_Y^2)^2}, \qquad (9)$$

$\bar{J}$ is a constant parametrizing the cuspiness of our galaxy's dark-matter halo, $\Delta\Omega$ is the experiment's solid angle, and $N_\gamma = \int_{E_{\rm thr}}^{m_X} dE \frac{dN_\gamma}{dE}$ is the average number of photons above threshold produced in each τ decay.

In Fig. 3, we evaluate the discovery prospects for the Fermi Gamma-Ray Space Telescope (Fermi) [22]. We take $\Delta\Omega = 0.001$, $N_\gamma = 1$, and $E_{\rm thr} = 1$ GeV, and require $\Phi_\gamma > 10^{-10}\ {\rm cm^{-2}\, s^{-1}}$ for discovery. The minimum values of $\bar{J}$ for discovery for various λ_τ as a function of m_X are given in Fig. 3. As the flux is proportional to number density squared, we find excellent discovery prospects for light dark matter. For $\lambda_\tau = 0.3$ and $m_X \lesssim 20$ GeV, Fermi will see signals for $\bar{J} \sim 1$, corresponding to smooth halo profiles that are inaccessible in standard WIMP models.

Conclusions.—In GMSB models with hidden sectors, we have found that, remarkably, any stable hidden sector particle will naturally have a thermal relic density that approximately matches that observed for dark matter. Indeed, it is merely an accident that the MSSM itself has no stable particle with the right relic density in GMSB, and it is an accident that need not occur in hidden sectors. These candidates possess all the key virtues of conventional WIMPs, but they generalize the WIMP paradigm to a broad range of masses and gauge couplings. This generalization opens up new possibilities for large dark-matter

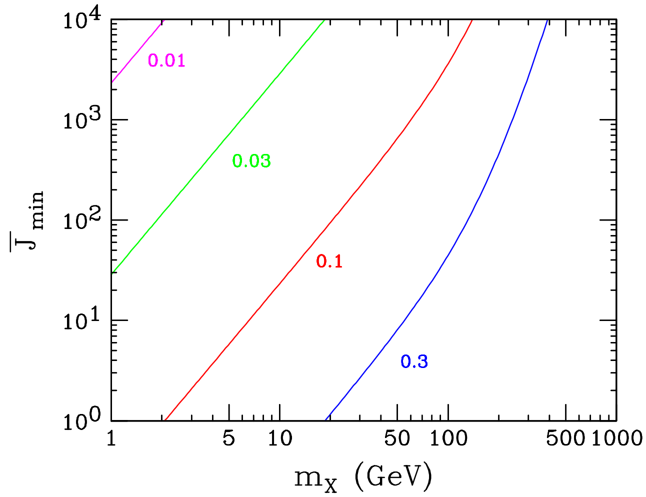

FIG. 3 (color online). Indirect detection prospects for WIMPless dark matter as a function of dark-matter mass m_X. For values of $\bar{J}$ above the contours, the annihilation process $X\bar{X} \rightarrow \tau\bar{\tau}$ yields an observable photon signal at GLAST. We assume connector mass $m_{Y_\tau} = 200$ GeV and the Yukawa couplings λ_τ indicated.

signals. We have illustrated this with two examples, but many other signals are possible.

As shown in Fig. 1, this scenario also naturally accommodates multicomponent dark matter if there are multiple hidden sectors. This is highly motivated—in IBMs, one generally expects multiple hidden sectors in addition to the MSSM. In this framework, it is completely natural for dark-matter particles with varying masses and couplings to each be a significant component of dark matter.

Finally, dark matter with no WIMPs introduces new possibilities for the interplay between colliders and dark-matter searches. For example, LHC evidence for GMSB would exclude neutralino dark matter, but favor WIMPless (and other) scenarios. Further evidence from direct and indirect searches, coupled with Tevatron or LHC discoveries of "4th generation" quarks or leptons, could disfavor or establish the existence of WIMPless dark matter and the accompanying connector sectors.

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