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CoGeNT, DAMA, and light neutralino dark matter

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ABSTRACT

Recent observations by the CoGeNT collaboration (as well as long standing observations by DAMA/LIBRA) suggest the presence of a ~ 5–10 GeV dark matter particle with a somewhat large elastic scattering cross section with nucleons ($\sigma \sim 10^{-40}$ cm^2). Within the context of the minimal supersymmetric standard model (MSSM), neutralinos in this mass range are not able to possess such large cross sections, and would be overproduced in the early universe. Simple extensions of the MSSM, however, can easily accommodate these observations. In particular, the extension of the MSSM by a chiral singlet superfield allows for the possibility that the dark matter is made up of a light singlino that interacts with nucleons largely through the exchange of a fairly light (~ 30–70 GeV) singlet-like scalar higgs, h_1. Such a scenario is consistent with all current collider constraints and can generate the signals reported by CoGeNT and DAMA/LIBRA. Furthermore, there is a generic limit of the extended model in which there is a singlet-like pseudoscalar higgs, a_1, with $m_{a_1} \sim m_{h_1}$ and in which the $\chi^0\chi^0$ and $b\bar{b}$, $s\bar{s}$ coupling magnitudes of the h_1 and a_1 are very similar. In this case, the thermal relic abundance is automatically consistent with the measured density of dark matter if m_{χ^0} is sufficiently small that $\chi^0\chi^0 \to b\bar{b}$ is forbidden.

Recently, the CoGeNT collaboration has reported the detection of very low energy events which cannot be accounted for with known backgrounds [1]. It has been shown than it is possible to interpret these events as the elastic scattering of a light dark matter particle ($m \sim 5$–10 GeV) with a cross section on the order of $\sim 10^{-40}$ cm^2 [1–5]. Intriguingly, the range of masses and cross sections implied by CoGeNT is not very far from the region required to explain the annual modulation observed by the DAMA/LIBRA collaboration [6–8]. While null results from liquid XENON-based experiments [9] and CDMS [10] somewhat constrain dark matter interpretations of the CoGeNT and DAMA/LIBRA signals, uncertainties in the dark matter velocity distribution, as well as the various experiments' energy scale calibrations and quenching factors (and/or scintillation efficiencies) could potentially lead to a consistent interpretation [5,11].

Since the announcement of the CoGeNT result, a number of groups have begun to explore the dark matter phenomenology of this signal [5,12–14]. Within the context of the Minimal Supersymmetric Standard Model (MSSM), dark matter explanations for the CoGeNT/DAMA signals face considerable challenges. The range of elastic scattering cross sections predicted for neutralinos falls more than an order of magnitude short, even in the most optimal regions of parameter space [15,16]. While this could plausibly be reconciled by adopting a significantly higher local density of dark matter (the required cross section scales inversely with the local dark matter density), the relic abundance of very light (5–10 GeV) neutralinos in the MSSM is also predicted to be well above the measured cosmological dark matter density [16] (for earlier work on light neutralino dark matter in the MSSM, see Ref. [17]). Thus, even in optimistic regions of the MSSM parameter space, it is very difficult to accommodate the observations of CoGeNT and DAMA/LIBRA.

To increase the elastic scattering cross section and reduce the thermal relic abundance of neutralino dark matter, one could consider a combination of larger couplings or lower masses for the particles exchanged. However, for very light neutralinos (whose scattering is typically dominated by scalar higgs bosons) this prospect is constrained by Tevatron and LEP II data which require the masses of MSSM higgs bosons to lie above $\gtrsim 90$ GeV. However, the constraints need not apply in supersymmetric models with extended higgs sectors [18]. As we will show, in such scenarios it is possible for a 5–10 GeV neutralino to produce the observed signal through the exchange of a light (~ 30–70 GeV) scalar higgs, while also generating the correct thermal relic abundance.

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Generically, the spin-independent elastic scattering cross section of dark matter with a nucleus is written:

$$\sigma \approx \frac{4m_{\mathrm{DM}}^2 m_N^2}{\pi (m_{\mathrm{DM}}+m_N)^2}\big[Zf_p+(A-Z)f_n\big]^2, \tag{1}$$

where m_N is the mass of the target nucleus (of atomic number Z and mass A), and m_{DM} is the dark matter mass. f_p and f_n are the dark matter's couplings to protons and neutrons:

$$f_{p,n} = \sum_{q=u,d,s} f_{T_q}^{(p,n)} a_q \frac{m_{p,n}}{m_q} + \frac{2}{27} f_{TG}^{(p,n)} \sum_{q=c,b,t} a_q \frac{m_{p,n}}{m_q}, \tag{2}$$

where a_q are the dark matter's couplings to quarks (in the Lagrangian) and $f_{T_q}^{(p,n)}$, $f_{TG}^{(p,n)}$ are hadronic matrix elements [19]. An appropriate nuclear form factor accounts for the effects of finite momentum transfer. We use the values $f_{T_u}^{(p)} = 0.020 \pm 0.004$, $f_{T_s}^{(p)} = 0.026 \pm 0.005$, $f_{T_s}^{(p)} = 0.118 \pm 0.062$, $f_{T_s}^{(p)} = 0.118$ and $f_{TG}^{(p)} = 0.84$ [20]. The uncertainties in determination of hadronic matrix elements, which are due to the uncertainty in determination of $\sigma_{\pi N}$, might reach approximately a factor of two and therefore result in a factor of two uncertainty in the dark matter couplings.

For light MSSM neutralinos, the neutralino-quark coupling is dominated by scalar higgs exchange (contributions from squark exchange are typically negligible). For down-type quarks, this coupling is [20]:

$$\frac{a_d}{m_d} = \frac{g_2}{4m_W \cos\beta}[-g_1 N_{11} + g_2 N_{12}] \times \left[\left(\frac{N_{13}c_\alpha^2 - N_{14}c_\alpha s_\alpha}{m_H^2}\right) + \left(\frac{N_{13}s_\alpha^2 + N_{14}c_\alpha s_\alpha}{m_h^2}\right)\right], \tag{3}$$

where the N_{1i}'s denote the composition of the lightest neutralino ($\chi_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u$), and s_α and c_α denote the sine and cosine of α, which relate the scalar mass and gauge eigenstates. The corresponding expression for up-type quarks is found by replacing $\cos\beta \leftrightarrow \sin\beta$ and $N_{14} \leftrightarrow N_{13}$.

The largest elastic scattering cross sections in the MSSM arise in the case of large $\tan\beta$ and $\sin(\beta-\alpha) \sim 1$, significant N_{13}, and relatively light m_H. In this limit, the lighter higgs, h, is approximately standard model-like and the heavier H is approximately H_d, and one finds

$$\frac{a_d}{m_d} \approx \frac{-g_2 g_1 N_{13} N_{11} \tan\beta\, c_\alpha^2}{4m_W m_H^2}, \tag{4}$$

which in turn yields

$$\sigma_{\chi^0 p,n} \approx 1.8 \times 10^{-41}\ \mathrm{cm}^2 \left(\frac{N_{13}^2}{0.103}\right)\left(\frac{\tan\beta}{50}\right)^2 \times \left(\frac{90\ \mathrm{GeV}}{m_H}\right)^4 \left(\frac{c_\alpha}{1}\right)^4, \tag{5}$$

where the reference values for the Higgs mass, $\tan\beta$, N_{13}^2 and c_α have been chosen in the most optimistic way as discussed below.

The higgsino content of the lightest neutralino is constrained by the invisible width of the Z as measured at LEP, $\Gamma_{\mathrm{inv}}^{\mathrm{LEP}} = 499 \pm 1.5$ MeV. In contrast, the standard model prediction for this quantity is slightly (1.4σ) higher, $\Gamma_{\mathrm{inv}}^{\mathrm{SM}} = 501.3 \pm 0.6$ MeV [21]. Combining the measured and predicted values, we find a 2σ upper limit of $\Gamma_{Z\to\chi^0\chi^0} < 1.9$ MeV. As $\Gamma_{Z\to\chi^0\chi^0}$ scales with $[N_{13}^2 - N_{14}^2]^2$, we can translate this result to a limit of $|N_{13}^2 - N_{14}^2| < 0.103$. For moderately large values of $\tan\beta$, the two higgsino terms do not efficiently cancel, requiring $|N_{13}|^2 < 0.103$.

m_H and $\tan\beta$ are constrained by a number of measurements, including those of the rare decays $t \to bH^+$, $B_s \to \mu^+\mu^-$, $B^\pm \to \tau\nu$, and direct limits on higgs production followed by $A/H \to \tau^+\tau^-$. While these limits vary somewhat depending on the precise values of the MSSM parameters adopted, in general they imply $\tan\beta \lesssim 20$–30 for $m_H, m_A \sim 90$–150 GeV (the strongest limits coming from the latest LHC results). Constraints from LEP II further require $m_{H,A} \gtrsim 90$ GeV. When these limits are taken into account, we find that $\sigma_{\chi^0 p,n} \lesssim 10^{-41}\ \mathrm{cm}^2$ [15,16], which falls short of that implied by the CoGeNT and DAMA/LIBRA signal by about an order of magnitude.

Furthermore, light neutralinos in the MSSM are inevitably predicted to freeze out with a thermal relic abundance in excess of the measured dark matter density. Indeed, there is a kind of inverse relation whereby for $m_H \sim m_A$ near 90 GeV, appropriate $\Omega_{\chi^0}h^2$ from annihilation via the A to $b\bar{b}$ and $\tau^+\tau^-$ is roughly proportional to the inverse of $\sigma_{\chi^0 p,n}$ and only falls to a value of order $\Omega_{\chi^0}h^2 \sim 0.1$ when $\sigma_{\chi^0 p,n}$ is of order the maximal value indicated above. Given that current experimental constraints in the MSSM context do not allow one to achieve this maximal value, the MSSM inevitably leads to too large a value for $\Omega_{\chi^0}h^2$. Increasing m_A or m_H worsens the situation.

To increase the cross section beyond the range allowed in the MSSM, an obvious direction is to consider models with lighter higgs bosons. As the cross section scales with the inverse of the fourth power of the exchanged higgs mass, even modest reductions in m_H could increase the cross section to the levels required. As an example of a framework in which light higgs bosons are possible, we extend the MSSM by a chiral singlet superfield $\hat{S}$, containing two neutral scalars H_S and A_S and a Majorana fermion $\tilde{S}$. The theory is described by superpotential [22]

$$\frac{1}{2}\mu_S \hat{S}^2 + \mu \hat{H}_u \hat{H}_d + \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{1}{3}\kappa \hat{S}^3 \tag{6}$$

(along with the MSSM Yukawa interactions), and soft Lagrangian

$$\mathcal{L}_{soft} = v_S^3 S + B_\mu H_u H_d + \frac{1}{2}m_S^2|S|^2 + \frac{1}{2}B_S S^2 + \lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + \mathrm{H.c.} \tag{7}$$

(along with the MSSM A-terms). Specific implementations of such a singlet typically involve a subset of these terms. For example, in the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [23], a Z_3 symmetry is imposed which only allows the terms involving λ, κ, A_λ and A_κ. Here, we do not tie ourselves to this particular model, but instead consider the full range of terms as described in Eqs. (6) and (7), which we refer to as the Extended Next-to-Minimal Supersymmetric Standard Model (ENMSSM).

The tree-level neutralino mass matrix in the $\tilde{B}$, $\tilde{W}^3$, $\tilde{H}_u$, $\tilde{H}_d$, $\tilde{S}$ basis is

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & \frac{g_1 v_u}{\sqrt{2}} & -\frac{g_1 v_d}{\sqrt{2}} & 0 \\ 0 & M_2 & -\frac{g_2 v_u}{\sqrt{2}} & \frac{g_2 v_d}{\sqrt{2}} & 0 \\ \frac{g_1 v_u}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 & -\mu-\lambda s & -\lambda v_d \\ -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_2 v_d}{\sqrt{2}} & -\mu-\lambda s & 0 & -\lambda v_u \\ 0 & 0 & -\lambda v_d & -\lambda v_u & 2\kappa s + \mu_S \end{pmatrix}, \tag{8}$$

where v_u and v_d are the up- and down-type higgs vevs and s is the vev of the singlet higgs. A light ($\lesssim 10$ GeV) neutralino consistent with LEP II chargino searches must be either mostly $\tilde{B}$ or $\tilde{S}$. The $\tilde{B}$ does not couple to a mostly singlet higgs, and that case is thus similar to the MSSM. From here on, we focus on the case where the lightest neutralino is mostly $\tilde{S}$. One might imagine that the strict NMSSM would allow sufficient flexibility. It has been shown [24] that for the bulk of the NMSSM, after imposing LEP and B-physics constraints the lightest neutralino is always bino-like and elastic cross sections as large as required by CoGeNT and DAMA/LIBRA are not possible. Nonetheless they are "only" a factor of 10 too small (whereas in Ref. [25] the largest cross section found was a factor of 100 too small). An exception to this conclusion was identified in Ref. [26], in which a very light (~GeV) singlet scalar higgs is able to generate the very large elastic scattering cross section required by CoGeNT and DAMA/LIBRA within the context of the NMSSM. These scenarios require a considerable degree of fine-tuning of the parameters. As we show, in the ENMSSM, it is possible to find less fine-tuned scenarios with large elastic cross section and correct relic density when the light higgs has mass $\gtrsim 30$ GeV even when $\tan\beta$ is small enough to evade the most recent LHC limits on Higgs bosons with enhanced $b\bar{b}$ couplings proportional to $\tan\beta$.

We proceed by engineering the lightest neutralino to be mostly $\tilde{S}$, together with a light higgs that is predominantly singlet. The lightest neutralino will naturally be predominantly singlino provided the quantity $|2\kappa s + \mu_S|$ is much smaller than $|\mu + \lambda s|$, M_1 and M_2. For example, for $\kappa \sim 0.45$, $s \sim 2$ GeV, $\mu_S \approx 0$, $\lambda \sim 0.01$, $\tan\beta \sim 15$, large M_1, large M_2, and $\mu \sim 180$ GeV, we find that the lightest neutralino is singlino-like ($N_{15}^2 = 0.99$) with a mass of approximately 5 GeV.

The conditions under which the lightest higgs, h_1, is mostly singlet are somewhat more complicated. A simple limit which leads to desired phenomena can be obtained for small λ. In the limit $\lambda \to 0$, but keeping λA_λ of moderate size, the singlet decouples from the MSSM (which has standard higgses), and has a mass determined primarily by the $\lambda A_\lambda v^2 \sin 2\beta/(2s)$ singlet-singlet entry in the mass-squared matrix, with weak dependence on B_S, m_S^2, μ_S, κ, and A_κ. Then, provided the soft terms for the singlet are sufficiently small, and λv is much smaller than m_h, the singlet represents a perturbation on MSSM higgs phenomenology, with a light singlet state mixed with the MSSM to a degree controlled by λ. In this limit, the light CP odd higgs will also be predominantly singlet, with mass and mixings to the MSSM A that are proportional to $\lambda A_\lambda v^2 \sin 2\beta/(2s)$ *with the same coefficients as for the* h_1. Effectively, the h_1 and a_1 combine to form a single complex nearly singlet scalar state. Through mixing with the MSSM higgses, both the h_1 and a_1 have couplings proportional to the usual MSSM interactions, but reduced by the small amount of mixing. For the parameters listed earlier, along with $A_\kappa \sim 33$ GeV, $A_\lambda \sim 3400$ GeV, $B_S \sim 0$, $m_S^2 \sim 0$ one finds $m_{h_1} \sim 40$ GeV, $m_{a_1} \sim 35$ GeV with $|F_s(h_1)|^2 \sim |F_s(a_1)|^2 \sim 0.65$ and $|F_d(h_1)|^2 \sim |F_d(a_1)|^2 \sim 0.35$, where $F_s(h_1)$ and $F_d(h_1)$ are the singlet and H_d^0 components (at the amplitude level) of the h_1 and $F_s(a_1)$ and $F_d(a_1)$ are the singlet and A_d^0 components of the a_1. To reemphasize, in the scenarios we consider the a_1 and h_1 are close in mass and have F_s and F_d components that are very similar.

The singlino coupling to down-type quarks via h_1 exchange at Lagrangian level is given by

$$\frac{a_d}{m_d} = \frac{g_2 \kappa N_{15}^2 F_s(h_1) F_d(h_1)}{2\sqrt{2} m_W m_{h_1}^2 \cos\beta}. \tag{9}$$

For h_1 exchange only, the resulting spin-independent cross section is

$$\sigma_{\chi^0 p,n} \approx 3.3 \times 10^{-40}\ \text{cm}^2 \left(\frac{\kappa}{0.4}\right)^2 \left(\frac{\tan\beta}{15}\right)^2 \times \left(\frac{40\ \text{GeV}}{m_{h_1}}\right)^4 \left(\frac{|F_s(h_1)|^2}{0.65}\right)\left(\frac{|F_d(h_1)|^2}{0.35}\right), \tag{10}$$

which is of order the value required by CoGeNT and DAMA/LIBRA. Furthermore, the mostly singlet nature ($|F_s(h_1)|^2 \sim 0.65$) of the h_1 easily allows it to evade the constraints from LEP II and the Tevatron, as we discuss below. The fact that moderately large $|F_d(h_1)|^2$ is required argues that this scenario will be difficult to arrange in the (MSSM) decoupling regime of $m_{a_2} \gg m_{h_2}$, implying that all of the mostly MSSM higgses are likely to have masses only slightly above the LEP II limit. In fact, for the parameters listed above, $m_{h_2} \sim 109$ GeV (but escapes LEP limits since it has substantial singlet component, $|F_s(h_2)|^2 \sim 0.28$), $m_{a_2} \sim 111$ GeV and $m_{h_3} \sim m_{h^+} \sim 125$ GeV. After including h_2 and h_3 in the computation of $\sigma_{\chi^0 p,n}$ the coefficient of 3.3 is reduced to about 2.2 in Eq. (10) due to some partial cancellation at the amplitude level.

Collider constraints on the h_1 and h_2 are largely evaded for sufficiently small $|F_s(h_1)|$ and $|F_s(h_2)|$. LEP II places constraints through production of Zh_i (for the scalars) and pair production of $a_i h_j$ for the pseudoscalars. The heavier mass eigenstates (h_3, and a_2) look like their MSSM counterparts, with their couplings slightly reduced by a small singlet component. Thus, provided they represent a viable point of MSSM parameter space, they will be allowed here as well. The light (mostly singlet) h_1 and a_1 must have small enough Z–Z–h_1 and Z–h_i–a_1 interactions to be consistent with existing searches. In the scenarios considered here, the coupling of the h_1 to WW, ZZ (relative to the SM coupling), denoted $C_V(h_1)$, is very small, $|C_V(h_1)| < 0.1$, which easily allows $m_{h_1} \sim 40$–50 GeV to be consistent with LEP limits on Zh_1 [27]. Small $|C_V(h_1)|$ arises in the limit $A_\lambda \gtrsim \mu$. The Z–h_1–a_1 coupling is similarly suppressed implying that LEP limits on $h_1 a_1$ pair production are easily evaded. Pair production of a_1 together with the mostly SM-like light higgs h_2 is sufficiently suppressed by the largely singlet nature of the a_1. The Tevatron can produce scalars and pseudoscalars through the reaction $bg \to b + h, a$, where the h or a can decay into either $b\bar{b}$ or $\tau^+\tau^-$ pairs. In our scenarios, the strongest constraints arise for $h = h_3$ and $a = a_2$ since they are fairly light and mainly non-singlet and have $b\bar{b}$ couplings that are enhanced at large $\tan\beta$. Null LHC searches with $L = 1\ \text{fb}^{-1}$ of accumulated luminosity at CMS require $\tan\beta \lesssim 25$ for a doublet-like h_3 or a_2 with (non-degenerate) masses of order 100 GeV [28]. A similar limit on $\tan\beta$ can be obtained from the null search for $t \to H^+ b$ [29]. Taken all together, the central parameters of Eq. (10) are on the border of a number of higgs searches, and are thus being tested by end-phase Tevatron and early LHC running.

The thermal relic density of neutralinos is determined by the annihilation cross section and neutralino mass. In the m_{χ^0} range we are considering here, the potentially important annihilation channels are to $b\bar{b}$ or $\tau^+\tau^-$ through the s-channel exchange of Higgs bosons. Given that $m_{h_1} \sim m_{a_1}$ and that the F_s and F_d components of the h_1 and a_1 are similar, the CP-odd a_1 is dominant, annihilation via the CP-even h_1 being p-wave (v^2) suppressed.[1] The annihilation cross section for the $b\bar{b}$ final state that results from s-channel exchange of the a_1 is given by

$$\sigma v = \frac{N_c g_2^2 \kappa^2 m_b^2 |F_s(a_1)|^2 |F_d(a_1)|^2}{4\pi m_W^2 \cos^2\beta} \times \frac{m_{\chi^0}^2 (1 - m_b^2/m_{\chi^0}^2)^{1/2}}{(4m_{\chi^0}^2 - m_{a_1}^2)^2 + m_{a_1}^2 \Gamma_{a_1}^2}, \tag{11}$$

where v is relative velocity between the annihilating neutralinos, $N_c = 3$ is a color factor and Γ_{a_1} is the width of the exchanged higgs. The annihilation cross section into $\tau^+\tau^-$ is obtained by re-

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[1] This differs from the scenario of [26] in which the a_1 is highly singlet and annihilation is dominated by the h_1.

placing $m_b \to m_\tau$ and $N_c \to 1$. The thermal relic abundance of neutralinos is obtained as

$$\Omega_{\chi^0} h^2 \approx \frac{10^9}{M_{\rm Pl}} \frac{m_{\chi^0}}{T_{\rm FO}\sqrt{g_\star}} \frac{1}{\langle \sigma_{\chi^0\chi^0} v\rangle}, \tag{12}$$

where $g_\star$ is the number of relativistic degrees of freedom available at freeze-out, $\langle \sigma_{\chi^0\chi^0} v\rangle$ is the thermally averaged annihilation cross section at freeze-out, and $T_{\rm FO}$ is the temperature at which freeze-out occurs. In the scenarios considered here, one finds that the annihilation rate is too large if the $a_1 \to b\bar{b}$ channel is open. As a result, consistency with the observed relic density is only "automatically" obtained if $m_{\chi^0} < m_b(pole) \simeq 5.28$ GeV.

For the range of masses and cross sections considered here, we find $m_{\chi^0}/T_{\rm FO} \approx 20$, leading to a thermal relic abundance from $a_1 \to \tau^+\tau^-$ of

$$\Omega_{\chi^0} h^2 \approx 0.15 \left(\frac{0.4}{\kappa}\right)^2 \left(\frac{15}{\tan\beta}\right)^2 \left(\frac{m_{a_1}}{35\ \text{GeV}}\right)^4 \times \left(\frac{5\ \text{GeV}}{m_{\chi^0}}\right)^2 \left(\frac{0.65}{|F_s(a_1)|^2}\right)\left(\frac{0.35}{|F_d(a_1)|^2}\right), \tag{13}$$

applicable so long as m_{χ^0} is small enough that the $b\bar{b}$ channel is not open. After including other exchanges, one obtains a value of $\Omega_{\chi^0} h^2$ that is consistent with the measured dark matter density, $\Omega_{\rm CDM} h^2 = 0.1131 \pm 0.0042$ [30].

Thus, the desired relic density automatically results at low m_{χ^0} once the relevant combination of couplings and higgs masses are set to accommodate CoGeNT and DAMA/LIBRA. This confluence of parameter space is peculiar to models with scalar/pseudoscalar exchange [2,31,32]. For example, a Dirac fermion or a scalar with vector interactions will either overproduce the CoGeNT and DAMA/LIBRA rates or will predict a thermal relic density in excess of the measured dark matter abundance.

This scenario also has interesting implications for the indirect detection of dark matter. In particular, as the dark matter annihilation rate in any given region scales with the inverse of the square of the dark matter mass, the light neutralino we are considering could, in principle, lead to enhanced fluxes of various annihilation products [33]. Quantitatively, the spectrum of gamma-rays from dark matter annihilations can be written as

$$\Phi_\gamma(E_\gamma, \psi) = \frac{dN_\gamma}{dE_\gamma} \frac{\sigma v}{8\pi m_{\chi^0}^2} \int_{\rm los} \rho^2(r)\, dl, \tag{14}$$

where σv is the dark matter annihilation cross section multiplied by the relative velocity of the two neutralinos, ψ is the angle observed relative to the direction of the Galactic Center, $\rho(r)$ is the dark matter density as a function of distance to the Galactic Center, dN_γ/dE_γ is the gamma ray spectrum generated per annihilation, and the integral is performed over the line-of-sight. For a neutralino with $m_{\chi^0} \sim 5$ GeV and with an annihilation cross section of $\sigma v \approx 3 \times 10^{-26}\ \text{cm}^3/\text{s}$ to $\tau^+\tau^-$, the annihilation rate in the Galactic Center (assuming an NFW halo distribution) is predicted to lead to a flux of gamma-rays above 1 GeV of $\approx 2.9\ \text{cm}^{-2}\,\text{yr}^{-1}$ from the inner degree of our galaxy, corresponding to thousands of events per year observed by the Fermi Gamma Ray Space Telescope (FGST). Furthermore, the flux and spectral shape of the gamma-ray emission observed by the FGST from this region of the sky is quite similar to that predicted from dark matter annihilations [35]. FGST's observations of dwarf spheroidal galaxies [34] are also potentially sensitive to a dark matter particle with these characteristics.

The prediction that the dark matter annihilates primarily to $\tau^+\tau^-$ also insures that our dark matter candidate will not violate constraints from cosmic ray antiproton measurements, as set by the PAMELA experiment [33,36,37]. If gamma ray searches for the products of dark matter annihilations were in the future to constrain the low-velocity annihilation cross section to be well below the value of $\sigma v \sim 3 \times 10^{-26}\ \text{cm}^3/\text{s}$, this would rule out the present model as well as the possibility that the dark matter is a scalar with scalar interactions [2,31,38].

Another indirect detection mode with decent prospects is to search for energetic neutrinos produced through the capture and annihilation of dark matter in the core of the Sun. The Sun is predicted to capture dark matter particles at a rate given by

$$C^\odot \simeq 3.5 \times 10^{24}\ \text{s}^{-1} \left(\frac{\rho_{\chi^0}}{0.4\ \text{GeV/cm}^3}\right)\left(\frac{270\ \text{km/s}}{\bar{v}}\right)\left(\frac{5\ \text{GeV}}{m_{\chi^0}}\right) \times \left[\left(\frac{\sigma_{\rm H}}{10^{-40}\ \text{cm}^2}\right) + 1.1\left(\frac{\sigma_{\rm He}}{16 \times 10^{-40}\ \text{cm}^2}\right)\right], \tag{15}$$

where ρ_{χ^0} is the local dark-matter density, $\bar{v}$ is the local root-mean-square velocity of halo dark-matter particles, and $\sigma_{\rm H}$ and $\sigma_{\rm He}$ are the elastic scattering cross sections of the WIMP with hydrogen and helium nuclei, respectively. In the model under consideration, the elastic scattering cross section of the neutralino is sufficiently large that the processes of capture and annihilation quickly reach equilibrium in the Sun, removing any dependence on the neutralino's annihilation cross section. The high capture rate in this model is predicted to produce a sizable flux of GeV-scale neutrinos, comparable to the constraints currently placed by Super-Kamiokande [2,39,40]. In particular, for $m_{\chi^0} \sim 5$ GeV and annihilation entirely to $\tau^+\tau^-$, Super-Kamiokande data can be used to constrain $\sigma_{\chi^0 p} \lesssim 6 \times 10^{-41}\ \text{cm}^2$ [2], for reasonable astrophysical assumptions. Larger volume neutrino experiments such as IceCube have energy thresholds which are too high to observe the annihilation products of such light dark matter particles.

In summary, we have considered the possibility that neutralino dark matter is responsible for the signals reported by the CoGeNT and DAMA/LIBRA collaborations. Although, the elastic scattering cross section of neutralinos with nuclei in the MSSM is too small to account for these observations, the same conclusion is not necessarily reached in extended supersymmetric models. In particular, we have discussed models in which the MSSM is extended by a chiral singlet superfield. In such a model, a light singlino-like neutralino, which interacts with nuclei through the exchange of a largely singlet-like, scalar higgs, can possess an elastic scattering cross section capable of generating the observations reported by CoGeNT and DAMA/LIBRA. Furthermore, the scenarios considered automatically lead to a thermal relic abundance of neutralinos consistent with the observed density of dark matter for $m_{\chi^0} \lesssim 5$ GeV.

After the completion of this project, the CoGeNT collaboration reported the detection of an annual modulation of their rate at the level of 2.8σ [41]. This result provides further motivation for the type of model considered in this Letter.

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