Target dark matter detection rates
in models with a well-tempered neutralino

Howard Baer\textsuperscript{a,b}, Azar Mustafayev\textsuperscript{c}, Eun-Kyung Park\textsuperscript{b} and Xerxes Tata\textsuperscript{d}

\textsuperscript{a}Department of Physics, University of Wisconsin, Madison, WI 53706, USA
\textsuperscript{b}Department of Physics, Florida State University, Tallahassee, FL 32306, USA
\textsuperscript{c}Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA
\textsuperscript{d}Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA

E-mail: baer@hep.fsu.edu, amustaf@ku.edu, epark@hep.fsu.edu, tata@phys.hawaii.edu

Abstract: In the post-LEP2 era, and in light of recent measurements of the cosmic abundance of cold dark matter (CDM) in the universe from WMAP, many supersymmetric models tend to predict 1. an overabundance of CDM and 2. pessimistically low rates for direct detection of neutralino dark matter. However, in models with a “well-tempered neutralino”, where the neutralino composition is adjusted to give the measured abundance of CDM, the neutralino is typically of the mixed bino-wino or mixed bino-higgsino state. Along with the necessary enhancement to neutralino annihilation rates, these models tend to give elevated direct detection scattering rates compared to predictions from SUSY models with universal soft breaking terms. We present neutralino direct detection cross sections from a variety of models containing a well-tempered neutralino, and find cross section asymptotes with detectable scattering rates. These asymptotic rates provide targets that various direct CDM detection experiments should aim for. In contrast, in models where the neutralino mass rather than its composition is varied to give the WMAP relic density via either resonance annihilation or co-annihilation, the neutralino remains essentially bino-like, and direct detection rates may be below the projected reaches of all proposed experiments.

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1. Introduction

One of the compelling successes of $R$-parity conserving supersymmetric models is the prediction of a candidate particle to account for cold dark matter (CDM) in the universe. The lightest neutralino $\tilde{\chi}_1$ is especially attractive [1, 2], since it could be produced thermally in the early universe with a cosmic abundance of the right order of magnitude to match precise measurements by the WMAP collaboration combined with data from the Sloan Digital Sky Survey which yield [3]

$$\Omega_{\text{CDM}} h^2 = 0.111^{+0.011}_{-0.015} \, (2\sigma). \quad (1.1)$$

The CDM relic abundance can be predicted in particle physics models with thermal WIMPs (such as the stable neutralino of supersymmetric models), where it is found that, aside from the additional complication of possible co-annihilation with electrically charged or colored sparticles or accidental resonance enhancements,

$$\Omega_{\text{WIMP}} h^2 \sim \frac{0.1 \text{ pb}}{\langle \sigma v_{\text{rel}} \rangle} \sim 0.1 \left( \frac{M_{\text{SUSY}}}{100 \, \text{GeV}} \right)^2, \quad (1.2)$$

where $\langle \sigma v_{\text{rel}} \rangle$ is the thermally averaged neutralino annihilation cross section times relative velocity, and $M_{\text{SUSY}}$ is the sparticle mass scale. Assuming no hierarchy in the sparticle spectrum, we see that sparticles with weak scale masses give the correct order of magnitude (1.1) for the relic density, whereas for much larger sparticle masses the predicted relic density will be too large unless the neutralino annihilation cross section in the early universe is enhanced from its naive value. The smallness of the error bars on the CDM relic density measurement provides a stringent upper bound on the relic CDM abundance predicted by supersymmetric models.\(^{1}\) The lower bound is less certain, since the dark matter may be comprised of several particles and the neutralino need not saturate the value in (1.1).

In early analyses of supersymmetric dark matter, the favored neutralino annihilation mechanism in the early universe was taken to be $\tilde{\chi}_1 \tilde{\chi}_1 \rightarrow f \bar{f}$ (where $f$ is a SM fermion), which occurs via $t$-channel sfermion exchange. Many analyses were performed within constrained frameworks where squark, slepton and gaugino mass parameters are related at some high energy scale, and where the sleptons tend to be lighter than squarks owing to renormalization group effects. Within such models, neutralino annihilation to leptons then has a larger cross section than annihilation to quarks since $m_{\tilde{\ell}} < m_{\tilde{q}}$. Assuming sfermion exchange as the dominant neutralino annihilation mechanism, the rather low value of $\Omega_{\text{CDM}} h^2$ measured by WMAP favors quite light sparticle masses $\sim 100$ GeV. At the same time, sparticle search limits from LEP2 require $m_{\tilde{\nu}_1} > 103.5$ GeV and $m_{\tilde{\ell}_{L,R}} > 99$ GeV, resulting in some tension between slepton-mediated annihilation scenarios and the WMAP/LEP2 data (see however Ref. [4] for some models where sfermion

\(^{1}\)Throughout our analysis, we assume thermal production of neutralinos and standard Big Bang cosmology, even at very early times in the history of the Universe. We recognise that it is possible to build phenomenologically viable models where the very early history of the Universe is significantly altered. In these more complicated cosmologies, our considerations would not apply [1].
exchange remains as the dominant neutralino annihilation channel in the early universe). As a result, the more generic prediction of constrained supersymmetric models today in the LEP2 allowed parameter space is an overabundance of CDM: see Eq. (1.2). In fact, it is only for special parameter choices where the neutralino annihilation cross section is enhanced, or where co-annihilation with colored or charged sparticles is important, that the model prediction is in accord with the measured abundance in (1.1).

The situation is exemplified in the extensively studied minimal supergravity model (mSUGRA)[6]. This model posits that the minimal supersymmetric standard model (MSSM) is the correct effective theory valid between mass scales $Q = M_{\text{GUT}}$ to $Q = M_{\text{weak}}$. It is assumed that SUSY breaking in a hidden sector induces universal soft SUSY breaking terms for visible sector fields via gravitational interactions. The effective Lagrangian for the visible sector, renormalized at a very high scale $Q \sim M_{\text{GUT}}$, is thus parametrized by a common mass parameter $m_0$ for all Higgs and matter scalars, a common mass $m_{1/2}$ for the SU(3), SU(2) and U(1) gauginos, and a common trilinear scalar coupling parameter $A_0$. The gauge and Yukawa couplings and soft SUSY breaking terms are then evolved via renormalization group equations (RGEs) from $M_{\text{GUT}}$ to $M_{\text{weak}}$, and electroweak symmetry is broken radiatively due to the large top Yukawa coupling. The model is completely defined by the well-known parameter set

$$m_0, \ m_{1/2}, \ A_0, \ \tan \beta \ \text{and} \ \text{sign}(\mu), \quad (1.3)$$

where $\tan \beta$ is the ratio of Higgs field vacuum expectation values $\tan \beta = v_d/v_u$, and $\mu$ is the superpotential Higgs mass term, whose magnitude (but not sign) is determined by the electroweak symmetry breaking minimization conditions.

The region of low $m_0$ and low $m_{1/2}$ (the so-called bulk region) of the mSUGRA model where neutralino annihilation via slepton exchange occurs[7], is nearly ruled out as already noted above. This leaves only several surviving regions in accord with (1.1): (1) co-annihilation regions at low $m_0$ where $m_{\tilde{\chi}_1} \simeq m_{\tilde{Z}_1}$[8, 9], or at particular $A_0$ values where $m_{\tilde{t}_1} \simeq m_{Z_1}$[10], (2) resonance annihilation regions such as the $A$-funnel[12], where $2m_{\tilde{Z}_1} \sim m_A, \ m_H$, and the $A (H)$-resonance enhances the neutralino annihilation rate, or the extremely narrow light Higgs corridor, where $2m_{\tilde{Z}_1} \simeq m_h$[13], and (3) the hyperbolic branch/focus point region (HB/FP) at large $m_0$, where $\mu$ becomes small and the neutralino acquires a significant higgsino component[14], which enhances its annihilation rate into vector bosons. Aside from these regions, most of the parameter space of the mSUGRA model is ruled out because the sparticle mass scale is too high resulting in a suppression of the annihilation rate and a corresponding over-abundance of CDM. Finally, we note that in mSUGRA, the $\tilde{Z}_1$ is dominantly bino-like over all of parameter space, with the exception being the HB/FP region, where it picks up a significant higgsino component, and becomes mixed higgsino dark matter (MHDM).

While the mSUGRA model serves as an economic paradigm for SUSY phenomenology in gravity-mediated SUSY breaking models, the assumption regarding universality at $Q = M_{\text{GUT}}$ is not well-motivated theoretically, and models with non-universal soft terms should be considered. In fact, patterns of non-universality generically arise in many SUSY GUT and string model incarnations. But what theoretical template is then suitable? In this
report, we will maintain the phenomenological successes of supersymmetric models, while extending the parameter space to allow various patterns of non-universality. Motivated by the successes of gauge coupling unification and the observed consistency of the light Higgs mass prediction \( m_h \lesssim 135 \text{ GeV} \) in the MSSM with precision electroweak measurements, we maintain the assumption that the MSSM is the correct effective theory between \( M_{\text{GUT}} \) and \( M_{\text{weak}} \). We also preserve the beautiful mechanism of radiative electroweak symmetry breaking (EWSB) triggered by the large top quark Yukawa coupling and associated renormalization group (RG) running of soft parameters from a high scale such as \( M_{\text{GUT}} \) to the weak scale \( M_{\text{weak}} \). We assume degeneracy of matter scalar soft terms equal to \( m_0 \) at \( M_{\text{GUT}} \) in order to suppress unwanted flavor-changing neutral current (FCNC) processes; Higgs boson soft mass parameters may, however, be assumed to be different from \( m_0 \). Also, even in grand unified models the three gaugino masses need not be unified at \( M_{\text{GUT}} \) (since SUSY breaking vevs need not necessarily respect the GUT symmetry). Finally, we assume standard Big Bang cosmology with the lightest neutralino as a thermal relic making up the bulk of CDM in the universe: \textit{i.e.} \( \Omega_{\tilde{Z}_1} h^2 \sim 0.11 \).

With the increased freedom in the GUT scale parameter space that is now possible with the relaxation of the various universality assumptions, we will be able to find scenarios such that the \( \tilde{Z}_1 \) gains a \textit{partial} wino or higgsino component: \textit{i.e.} just enough to fulfill the CDM relic density measurement \( [1] \). Models of this sort with mixed higgsino dark matter \( [13, 14, 17, 18, 19, 20] \) (MHDM) or mixed wino dark matter \( [21, 22] \) (MWDM) have been collectively dubbed models of a “well-tempered neutralino” in Ref. \( [23] \). While tempering will vary the neutralino composition to attain the measured relic density, it is alternatively possible to vary the neutralino mass: in this case, agreement with \( [1] \) may arise via resonant enhancement of the annihilation cross section, via stop or stau co-annihilation, or via the recently suggested bino-wino co-annihilation (BWCA) mechanism \( [24] \).

Since we will be working only with model parameter choices that completely saturate the WMAP measurement, we will be naturally interested in the associated direct detection of dark matter by underground experiments searching for relic neutralino-nucleus collisions. The spin-independent neutralino-proton elastic cross section, as a function of neutralino mass, serves as a figure of merit for direct detection experiments, and experimental sensitivities are usually shown as \( \sigma(\tilde{Z}_1 p) \text{ vs. } m_{\tilde{Z}_1} \), where effects of the specific nuclear target have been extracted. This allows for a direct comparison of the capabilities of detectors with different target materials. Predictions of direct detection scattering rates have been worked out by many groups for the mSUGRA model \( [25] \), as well as for models with non-universal soft terms \( [26, 27, 28] \). Frequently, if a model point yields a relic density \textit{in excess} of the value \( [1] \), it also tends to give extremely low direct detection rates, painting perhaps too pessimistic a picture for direct detection searches, given the WMAP constraint. By the same token, requiring a model with a well-tempered neutralino which yields the measurement \( [1] \), the mechanism which increases neutralino annihilation rates in the early universe may also increase the direct detection rates. This is the case if we start with a bino-like \( \tilde{Z}_1 \), and then temper it by adding just enough of either a higgsino component, and in some cases even a wino component, so as to saturate Eq. \( [1] \). Large direct detection
rates are generally not expected if the neutralino relic density is brought into agreement via neutralino co-annihilation with other charged or colored sparticles, or even via BWCA.

2. Direct detection cross sections in models with a well-tempered neutralino

We begin with a brief overview, in Fig. 1, of the current experimental upper limits on the spin-independent neutralino-proton cross section $\sigma_{SI}(\tilde{Z}_1 p)$ vs. $m_{\tilde{Z}_1}$, along with projections for their upgrades and other proposed experiments. Currently the most stringent upper limit on direct detection of neutralinos has been obtained by the CDMS experiment,[29] a cryogenic solid-state apparatus in the Sudan mine using Si and Ge targets. This limit, shown by the solid contour labelled CDMS, extends down to cross sections of $\sigma(\tilde{Z}_1 p) \sim 3 \times 10^{-7}$ pb for $m_{\tilde{Z}_1} \sim$ 100 GeV, and to about $2 \times 10^{-6}$ pb for TeV neutralinos. Since the experiments are based on the measurement of the recoil energy of the nucleus which, of course, reduces with increasing neutralino mass, the limits become weaker (and ultimately saturate) for neutralinos that are much heavier than the nucleus. The goal of CDMS II, as well as of Edelweiss II[30] and Cresst II[31], is to achieve optimal sensitivities of $\sim 10^{-8}$ pb by 2007-2008, as shown in the curve labelled CDMS II. In the long-term, CDMS plans to deploy 7 supertowers in the Sudbury mine site in a set-up labelled SuperCDMS, and aims to achieve a sensitivity as low as $10^{-9}$ pb by around 2012[32]. At the same time, a variety of projects are planned to construct large noble gas dark matter detectors, using xenon[33, 34], argon[35, 36] and/or neon[36] targets. Such detectors are cost-efficient, and can be envisaged to reach the ton scale in target material, and in addition may have neutron veto capabilities. Without making any representation of the feasibility of such detectors, we also show the projected reach in Fig. 1 of the Warm Argon Project (WARP), 1400 kg detector, which aims for a sensitivity of $10^{-10}$ pb, as indicative of this class of detectors.

In addition to the various experimental sensitivities in Fig. 1, we also show the expectation for the neutralino-proton direct detection cross section in various models, but only for parameter choices that give the neutralino relic density in agreement with (1.1). We take $m_t = 171.4$ GeV in our analysis [37]. Specifically, for each model we generate parameter space points, and then use Isajet v7.74 for the calculation of the sparticle mass spectrum and the associated neutralino relic density[38]. Then, for those points where the latter is compatible with its observed value, we extract the spin-independent neutralino-proton scattering rate from the IsaReS subroutine[39] (a part of the Isatools package that includes the evaluation of relic density[10] and other low energy observables) and plot it in Fig. 1.

We begin by showing for reference the expectation for the direct detection cross section for the paradigm mSUGRA model for $\mu > 0$ (red points) and $\mu < 0$ (dark blue points). We scan over $m_0 : 0 - 5$ TeV, $m_{1/2} : 0.1 - 2$ TeV, $\tan \beta = 10, 30, 45, 50, 52$ and 55, and take $A_0 = 0$. For both signs of $\mu$, we see that points form two distinct branches. For positive $\mu$ (red points), the branch which extends from $\sigma \sim 4 \times 10^{-7}$ pb at low $m_{\tilde{Z}_1}$ to values below $10^{-10}$ pb for large $m_{\tilde{Z}_1}$ and is formed by bulk/stau co-annihilation and $A$-funnel points. The HB/FP points where $\tilde{Z}_1$ forms MHDM lie on the upper branch at roughly constant $\sigma \sim 2 \times 10^{-8}$ pb[39]. In this region, as higher values of $m_0$ and $m_{1/2}$ are probed,
Figure 1: Spin-independent neutralino-proton scattering cross section versus neutralino mass in various cases of models with a well-tempered neutralino. We also show reach and projected reach of CDMS, CDMS II, SuperCDMS and WARP 1400 kg detector. We take $m_t = 171.4$ GeV.

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an increasingly mixed bino/higgsino $\tilde{Z}_1$ is needed to maintain accord with [1,10]. As a result, the neutralino has a slightly increasing direct detection cross section. We note that it is precisely in this HB/FP region, which falls entirely within the range of Super-CDMS experiment, that the gluinos and squarks can be very heavy so that the direct detection of supersymmetric particles at the CERN LHC [11,12,13] is the most difficult, even with $b$-tagging capabilities of the LHC detectors [14]. We also show the mSUGRA expectation for $\mu < 0$ (blue points). The direct detection cross sections in the HB/FP branch are only slightly lower than for positive $\mu$, and should be within the projected detection capability of Super-CDMS. A striking feature is that the direct detection cross section for the stau-coannihilation/A-funnel branch falls below even the WARP sensitivity for neutralino masses bigger than just 300 GeV. The suppression of the cross section for negative $\mu$ for large squark masses (where direct detection is dominated by $h$ and $H$ exchanges between the nucleus and the neutralino) was also noted in Ref. [15], and is the result of several contributing factors: the neutralino coupling to $h$ is smaller for negative $\mu$ because of a cancellation between the $H_0^0$ and $H_0^2$ contributions to the coupling, there is a negative interference between the tree-level $h$ and $H$ diagrams, but most importantly, diagrams

$^2$Although $m_H \gg m_h$, for large values of $\tan \beta$ the $H$-mediated contributions to neutralino-nucleon scattering remain significant. This is because $h \sim H_0^0$ when $\tan \beta$ is large so that its coupling to the strange quark (which makes the dominant tree level contribution) is suppressed by the Higgs mixing angle, whereas $H \sim H_0^2$ has an essentially unsuppressed coupling to s-quarks.
where the Higgs bosons couple via the gluon content of the proton through quark loops interfere negatively (positively) with tree level diagrams where the Higgs bosons couple to the quark content of the proton when $\mu < 0$ ($\mu > 0$).

Next we turn to models with a well-tempered neutralino. In order to avoid extremely lengthy computer scans, for the most part we fix $A_0 = 0$, $\tan \beta = 10$ and take $\mu > 0$.

2.1 NUHM1 model: small $\mu$ case

The first model we investigate is the one extra parameter non-universal Higgs model (NUHM1)[17]. These models are inspired by SO(10) SUSY GUTs, wherein matter superfields belong to the 16-dimensional spinor representation of SO(10), while Higgs superfields belong to the 10-dimensional fundamental representation. To avoid unwanted FCNC effects, we retain $m_0$ as the common matter scalar mass parameter renormalized at $Q = M_{GUT}$, but now allow an independent SUSY breaking mass squared parameter $m_\phi^2$, which can take either sign, for both $H_u$ and $H_d$ fields. It has been shown in Ref. [17] that for any mSUGRA parameter subset of the NUHM1 parameter set, dialing $m_\phi^2 \gg m_0^2$ leads to a diminution of $\mu^2$, resulting in an increased higgsino-content of $\tilde{Z}_1$ which can then become MHDM. We scan over the mSUGRA $m_0$ vs. $m_{1/2}$ plane for $m_0 : 0 - 2$ TeV, $m_{1/2} : 0 - 1.5$ TeV with $A_0 = 0$, $\tan \beta = 10$ and $\mu > 0$, while tempering the $\tilde{Z}_1$ at every point by dialing $m_\phi^2 \gg m_0^2$ until $\Omega_{\tilde{Z}_1} h^2 \simeq 0.11$ is attained. The associated spin-independent direct detection cross sections are then plotted as green dots. We have checked that other values of $A_0$ and $\tan \beta$ give qualitatively similar results. We find that the direct detection cross sections lie along a band at $\sigma \sim 1 - 3 \times 10^{-8}$ pb, and so this example of a model with a well-tempered bino/higgsino neutralino lies almost entirely within the reach of SuperCDMS.

2.2 NUHM1 model: A-funnel case

Within the NUHM1 model framework, it is also possible to obtain agreement with (1.1) by dialing $m_\phi^2 \neq m_0^2$ to large negative values. In this case, the $\tilde{Z}_1$ remains nearly pure bino, but $m_A$ drops until $m_A \sim 2 m_{\tilde{Z}_1}$, so that the neutralino annihilation in the early universe is resonance-enhanced, even at low $\tan \beta$[17]. Since a pure bino does not couple to $h$ or $H$, we do not expect a significant direct detection cross section except perhaps when sfermions are also light. For this case- where $m_A$ rather than the $\tilde{\chi}$ content of $\tilde{Z}_1$ is varied- the expectation is shown by pink dots extending to rather low values below $10^{-10}$ pb, which is below the projected reach of even the WARP 1400 kg detector.

2.3 LM3DM model with MHDM:

In this model, instead of using non-universal scalars, we adopt non-universal gaugino masses. In particular, by taking $M_1 = M_2 \equiv m_{1/2}$ at the GUT scale, but by dialing $|M_3(\text{GUT})| << m_{1/2}$, we reduce the gluino and squark masses. This reduction in particle masses feeds into a reduction in the magnitude of the $\mu$ parameter via the coupled RGEs and the EW minimization conditions[20], resulting in MHDM consistent with (1.1) together with low gluino and squark masses relative to charginos and neutralinos. This
is called the “low $|M_3|$ dark matter model” (LM3DM). For each point in the mSUGRA $m_0$ vs. $m_{1/2}$ plane (again for $A_0 = 0$, $\tan \beta = 10$ and $\mu > 0$) we reduce $M_3 > 0$ until \((1.1)\) is satisfied, and show the corresponding direct detection cross section in Fig. 1 as tan points. We see in this model that there exists a dense upper band of cross sections where $|\mu|$ is small enough to be MHDM, where $\sigma(\tilde Z_1 p) \sim 2 - 5 \times 10^{-8}$ pb which again falls within the projected reach of SuperCDMS. There is also a lower band of tan points with lower direct detection cross sections where compatibility with \((1.1)\) requires only a small reduction in $|M_3|$ because annihilation via relatively light sleptons in the low $m_0$ region of the parameter space also helps to yield the WMAP value of the CDM density. Although the neutralino is bino-like, $\sigma(\tilde Z_1 p) \gtrsim 10^{-9}$ pb (within the WARP 1400 kg reach) in this region, presumably because of both a slightly enhanced higgsino content and a lighter squark mass (relative to mSUGRA). We have checked that these results are qualitatively independent of the sign of $M_3$. However, if we increase $\tan \beta$ to 30, while the upper band remains essentially fixed, the lower one becomes more diffuse and extends down to about $2 \times 10^{-10}$ pb for the highest values of $m_{\tilde Z_1}$.

### 2.4 Mixed wino dark matter model (MWDM)

In the MWDM model\([22]\), we may either take $M_1$(GUT) as a free parameter with $M_2 = M_3 \equiv m_{1/2}$ and raise it until, \textit{at the weak scale} $M_1 \sim M_2$ (MWDM1), or we can fix $M_1 = M_3 \equiv m_{1/2}$ and lower the GUT scale value of $M_2$ until again, \textit{at the weak scale}, $M_1 \sim M_2$ (MWDM2). In both cases, the near equality of weak scale bino and wino masses (with $|\mu|$ remaining large) results in an LSP that is a mixed bino-wino state with only a small higgsino admixture. The resulting mixed bino-wino $\tilde Z_1$ has an increased annihilation rate into $W^+W^-$ pairs (via chargino exchange).\(^3\) Co-annihilation effects may also be important. Within the MWDM framework, we can take any point in the $m_0$ vs. $m_{1/2}$ plane of mSUGRA, and pull either $M_1$ up or $M_2$ down in value until we get a MWDM particle with $\Omega_{\tilde Z_1} h^2 \simeq 0.11$.

The direct detection cross sections from the WMAP-consistent points for the MWDM1 model (where $M_1$ is raised) are shown in Fig. 1 as yellow points. The striking feature is that the upper edge of the band of cross sections is detectable by Super-CDMS for all values of $\tilde Z_1$ masses. The direct detection cross section remains large in this band primarily because of the enhanced coupling of the lightest neutralino to $h$. This is due in part to the fact that as $M_1$ increases (while $\mu$ and $M_2$ stay essentially fixed), there is not only increased bino-wino mixing, but also bino-wino-higgsino mixing. Moreover, the relative sign of the bino and wino components of $\tilde Z_1$ is negative (it is positive for a pure photino state) so that the contribution from the neutral higgs-higgsino-bino and higgs-higgsino-wino \textit{add constructively} in the $h\tilde Z_1\tilde Z_1$ coupling.\([10]\) There is also a group of points with intermediate and low $m_{\tilde Z_1}$ that lie outside of the main yellow band. For those points, the $\tilde Z_1$ remains bino-like, and the WMAP value of relic density is achieved through various stau-coannihilation or A-funnel mechanisms. For these points, the above-mentioned cross

\(^3\)If $M_1 = M_2$ at the weak scale, the LSP is a photino with electromagnetic couplings to the $W^\pm W^\mp$ system, and the corresponding cross section for annihilation to $W$ bosons is governed by electromagnetic interactions.
section enhancements are absent, and direct detection of the neutralino would only be possible (if at all) at WARP 1400 kg. We have checked that if we increase $\tan \beta$ to 30, the upper portion of the main yellow band remains qualitatively unaltered (if anything, for very low $m_{\tilde{Z}_1}$, the cross section increases slightly), whereas the lower edge of this band now spreads down to $\sigma(\tilde{Z}_1 p) \sim 10^{-10}$ pb, so some points with $m_{\tilde{Z}_1} \sim 500$ GeV may not be within reach of the WARP 1400 kg detector. For these points, an increase of $M_1$ increases $m_{\tilde{Z}_1}$ until the A-funnel is reached before $\tilde{Z}_1$ becomes MWDM, so $\tilde{Z}_1$ remains bino-like. If instead, we take $\mu < 0$, the entire main yellow band shifts down and has $\sigma(\tilde{Z}_1 p) \leq 10^{-8}$ pb, so that super-CDMS becomes insensitive for $m_{\tilde{Z}_1} > \sim 500$ GeV, and a significant number of points closer to the lower edge of the yellow band fall below the reach of even the WARP 1400 kg experiment.

In the MWDM2 case where $M_2$ is lowered relative to fixed $M_1$ and $M_3$, we see that the direct detection cross section (shown by orange dots) falls off more rapidly with $m_{\tilde{Z}_1}$ than in the MWDM1 case. This is because gluinos and squarks, and hence $|\mu|$, are typically larger for a fixed LSP mass: as a result, the higgsino content of $\tilde{Z}_1$ is reduced (relative to the MWDM1 case). Furthermore, the wino content, while increased relative to mSUGRA, remains significantly smaller than in the MWDM1 case; the smaller wino component means that co-annihilations with $\tilde{W}_1$ and $\tilde{Z}_2$ are crucial in getting the right relic density, so in fact this case resembles BWCA dark matter, and the $\tilde{Z}_1$ is only slightly tempered. The small wino component of $\tilde{Z}_1$ results in a smaller coupling of the neutral Higgs bosons to $\tilde{Z}_1$ pairs compared to the MWDM1 case. The direct detection cross section, which becomes roughly comparable to that of the lower branch of the mSUGRA model, and may lie beyond even the reach of WARP 1400 kg for $m_{\tilde{Z}_1} \sim 350$ GeV.

### 2.5 Bino-wino co-annihilation (BWCA) dark matter model

The last method we study to get the observed value of the relic density is to allow $SU(2)$ and $U(1)$ gaugino masses with opposite signs, but with their weak scale magnitudes nearly equal: $|M_1(\text{weak})| \sim |M_2(\text{weak})|$. In this case, there is essentially no mixing between the bino and wino states and the $\tilde{Z}_1$ remains nearly a pure bino DM particle. However, since $m_{\tilde{W}_1} \sim m_{\tilde{Z}_2} \sim m_{\tilde{Z}_1}$, bino-wino co-annihilation can lower the LSP relic density to its measured value if $M_1$ or $M_2$ are appropriately adjusted. In the BWCA1 scenario, $M_1 < 0$ is adjusted for any fixed values of $M_2 = M_3 \equiv m_{1/2}$, while for the BWCA2 scenario, it is $M_2 < 0$ that is adjusted with $M_1 = M_3 \equiv m_{1/2}$. Because $\tilde{Z}_1$ remains bino-like, we expect the neutralino-nucleon scattering rate via Higgs boson exchange diagrams to be small, so that $\sigma(\tilde{Z}_1 p)$ will be relatively small unless squarks are very light. This is borne out by our analysis.

In Fig. we show the direct detection cross section for the BWCA2 model (light blue dots), where $-M_2$ is adjusted for a chosen value of $M_1 = M_3 \equiv m_{1/2}$. In this case, we see that the scattering rates are smaller than in the MWDM2 case, but may be observable at super-CDMS (WARP 1400 kg detector) if the LSP is lighter than 160 (300) GeV. The smallness of this cross section is primarily because the neutralino is essentially bino-like so that its higgsino components, which are essential in order for it to couple to $h$ or $H$,
are very small. Squark mediated contributions are usually much smaller. We have checked that the contributions from Higgs boson couplings to quarks interfere constructively with the corresponding (loop) contribution from its couplings to gluons, leading to the small, but possibly observable cross section.

Although we do not show results for the BWCA1 model where $M_1 < 0$ is adjusted to give the relic density, we have checked that the range of cross sections is qualitatively similar to the BWCA2 case except that even for small values of neutralino mass, the direct cross section can drop to well below $10^{-10}$ pb, so that it may not be detectable even at the WARP 1400 kg experiment. This is essentially for the same reasons (detailed above) that the cross section can be small for negative values of $\mu$ in the mSUGRA model. In the BWCA1 case, although $\mu > 0$, the relative sign between the mass parameter $M_1$ of the dominant gaugino component and $\mu$ is negative. The potential for the destructive interference between contributing diagrams means that although the cross section may be observable at the Super-CDMS (WARP 1400 kg) detector if $m_{\tilde{Z}_1} \leq 280$ GeV (400 GeV), direct detection rates could be below the sensitivity of the WARP 1400 kg experiment even for very low values of $m_{\tilde{Z}_1}$.

3. Conclusions

In general scans over the LEP2-allowed portions of parameter space of supersymmetric models with GUT scale universality (such as mSUGRA), the predicted neutralino relic density is usually considerably above the WMAP measurement (1.1), while the direct detection rates are pessimistically low. The predicted relic density matches its measured value only if one is in a region of co-annihilation, of resonance annihilation, or of mixed higgsino dark matter annihilation (such as the HB/FP region). In the last case, the predicted direct detection rates for WMAP allowed points in parameter space are roughly constant with $m_{\tilde{Z}_1}$ at a value $\sigma(\tilde{Z}_1p) \sim 10^{-8}$ pb. Usually, as one proceeds to higher values of $m_{\tilde{Z}_1}$, one has a falling direct detection cross section. However, in the HB/FP region, as $m_{\tilde{Z}_1}$ increases, an increasingly larger higgsino component of $\tilde{Z}_1$ is needed to maintain consistency with Eq. (1.1). The large higgsino component also contributes to a direct detection cross section which is large and relatively stable against variations in $m_{\tilde{Z}_1}$. The WMAP-allowed part of the HB/FP is an example of a region of parameter space where the composition of the neutralino is tempered to give the observed value of the CDM relic density. In the co-annihilation and resonance annihilation regions where sparticle masses are adjusted to give the measured relic density the neutralino remains a bino, and there is no enhancement of the direct detection cross section.

In our study, we have examined a variety of models where we extend the parameter space of the mSUGRA model, allowing either scalar mass or gaugino mass non-universality, to obtain agreement with (1.1). In well-tempered neutralino models where the composition of the neutralino is dialed to give the observed relic density, we typically get increased rates for neutralino direct detection because the coupling responsible for enhancement of the annihilation cross section frequently also enhances neutralino-nucleon scattering. More to the point, models of well-tempered neutralinos with mixed higgsino dark matter yield
neutralino-proton scattering cross sections that asymptote to $\sim 10^{-8}$ pb for large neutralino masses, within the sensitivity of the proposed 25 kg Super-CDMS upgrade of the CDMS experiment as illustrated in Fig. 1. Well-tempered neutralino models with mixed wino dark matter may also yield detectable values of $\sigma(\tilde{Z}_1 p)$ as illustrated by the MWDM1 model in this figure. These asymptotic values of $\sigma(\tilde{Z}_1 p)$ can serve as target cross sections that proposed experiments should aim to attain. In contrast, in the MWDM2 model, where the observed value of relic density is obtained more via co-annihilation processes, the wino-higgsino content of $\tilde{Z}_1$, and hence the direct detection cross section, remains relatively unenhanced.

In models where the mass – and not the composition – of the neutralino is varied to give the observed CDM relic density via resonance annihilation or via co-annihilation, the neutralino remains dominantly bino-like. In these cases, the direct detection cross sections do not asymptote with increasing $m_{\tilde{Z}_1}$, and we do not expect an enhancement of the direct detection rate, except for small parameter regions where sfermions are also very light.

In summary, we have shown that if relic dark matter consists predominantly of stable neutralinos that have been thermally produced in standard Big Bang cosmology, projections for the reach of direct dark matter detection experiments are substantially improved in supersymmetric models where the composition of the neutralino is adjusted to give the observed relic density. In this case, the neutralino will likely be detectable at proposed experiments. Unfortunately, there is no analogous improvement in the corresponding projections if the measured relic density is obtained by adjusting sparticle masses instead of the neutralino composition.

Acknowledgments

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References


[39] IsaReS, see H. Baer, C. Balazs, A. Belyaev and J. O’Farrill in Ref. 25.


[44] See P. Mercadante et al. in Ref. 12.
