Can neutralinos in the MSSM and NMSSM scenarios still be light?

Daniel Albornoz Vásquez,1,2 Geneviève Bélanger,2 Céline Brehm,2 Alexander Pukhov,3 and Joseph Silk4

1Astrophysics department, DWB building, Keble Road, OX1 3RH Oxford
2LAPTH, U. de Savoie, CNRS, BP 110, 74941 Annecy-Le-Vieux, France.
3Skobeltsyn Inst. of Nuclear Physics, Moscow State Univ., Moscow 119992, Russia
4Astrophysics department, DWB building, Keble Road, OX1 3RH Oxford, England
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Since the recent results of direct detection experiments at low mass, many authors have revisited the case of light (1-10) GeV WIMPs. In particular, there have been a few attempts to explain the results from the DAMA/LIBRA, CDMS and/or CoGeNT experiments by invoking neutralinos lighter than 15 GeV. Here we show that in the MSSM, such light particles are completely ruled out by the TEVATRON limits on the mass of the pseudoscalar Higgs. On the contrary, in the NMSSM, we find that light neutralinos could still be viable candidates. In fact, in some cases, they may even have an elastic scattering cross section on nucleons in the range that is needed to explain either the DAMA/LIBRA, CoGeNT or CDMS recent results. Finally, we revisit the lowest limit on the neutralino mass in the MSSM and find that neutralinos should be heavier than \( \sim 28 \text{ GeV} \) to evade present experimental bounds.

I. INTRODUCTION

Recently, both the CDMS and CoGeNT experiments have announced results which have been regarded as possible hints of the existence of dark matter particles. In particular, the CDMS experiment has claimed the detection of two “anomalous” events in a blind analysis [1] while the CoGeNT experiment has observed an unexplained rise in a p-type point contact (PPC) spectrum devoid of most surface events [2]. Together, these results might confirm the long-standing claims of detection of dark matter annual modulation by the DAMA/LIBRA experiment. Therefore, these findings deserve some attention.

The most puzzling aspect of these recent claims is that they seem compatible with the existence of rather light dark matter particles. For example, the assumption of dark matter particles with a mass between 7 and 11 GeV seems to provide a good fit to CoGeNT data (even though the null hypothesis also provides a similar fit) while particles from 7 GeV to 40 GeV could explain the CDMS events. This mass range is also compatible with the DAMA/LIBRA [3][4] findings which favour particles in the 10-15 GeV range assuming spin-independent (SI) interactions and no channeling.

Although these claims sound quite exciting, they raise several issues. First of all, CDMS claimed detection of two events only. This is not statistically significant to enable any firm conclusion related to dark matter. However, detection of more than five events would have been in conflict with the negative results of XENON 10 [5]. Secondly, the possible interpretation of a \( \sim 7 - 11 \) GeV dark matter candidate with a SI cross section around \( 10^{-41} - 10^{-40} \text{cm}^2 \) (as proposed by the CoGeNT collaboration) is severely challenged by the negative results of the XENON 100 experiment [6]. Nevertheless, it was also demonstrated that the uncertainties on the dark matter escape velocity \( v_{esc} \) and scintillation efficiency \( L_{eff} \) may offer a way to reconcile both XENON 100 and CoGeNT results [7][14]. Finally, the CDMS and CoGeNT events seem to exclude the high value of the spin-(in)dependent cross section that is favoured by the DAMA/LIBRA experiment. Nevertheless, it is worth mentioning that the mass range that is under consideration is not excluded neither by the ISR constraints at LEP [15] nor by the potential Sunyaev-Zel’ dovich effect that might be generated by relatively light dark matter particles in clusters of galaxies. [16][17]. Although it is premature to draw any conclusion about the nature of the DAMA/LIBRA, CDMS and CoGeNT results, it is certainly worth reinvestigating the possible dark matter candidates that are expected in the low mass region.

In this paper, we shall only consider supersymmetric candidates and in fact focus more specifically on the neutralino \( (\tilde{\chi}) \). We are seeking a light \( \tilde{\chi} \) with a relatively high elastic scattering cross-section with matter. In order to retain the connection with the “dark matter” interpretation, one should also require that this candidate has a relic density which represents a subsequent fraction (if not all) of the dark matter abundance inferred from the combination of CMB data with other cosmological (e.g. SN, BAO) observations [18].

Recently, the authors of Ref. [19] claimed that light neutralinos in MSSM-EWSB scenarios with non-universal gaugino masses could actually do the job. This work was followed by other claims (using supersymmetric extensions of the Standard Model [20][25]) to explain CoGeNT and/or CDMS events. However, light MSSM neutralinos were in fact investigated before these experimental claims [15][19][20][28] and just after the study of the astrophysical signatures that are to be expected from light WIMPs [29]. Neutralino masses down to \( \sim 5 \) GeV were found. However in Ref. [30], it was pointed out that the improved measurement of \( B_{\mu \mu} \) excludes such low neutralino masses. Very light neutralinos that would constitute hot dark matter were however found to be consistent with all experimental constraints [31].

Here, we reinvestigate the MSSM in light of the latest TEVATRON results to determine whether light neutralinos can explain the direct detection signals or not. We find that, when taking into account the Tevatron results on the supersymmetric Higgs at large values of \( \tan \beta \), the lower limit on the mass of the neutralino increases to 28 GeV. We then consider an extension of the MSSM with an extra singlet, the NMSSM. Neutralino dark matter in singlet extensions of the MSSM were first investigated in Ref. [32]. When the singlet Higgses are
light we find scenarios with neutralinos of a few GeV that evade all constraints and yet predict a direct detection signal in the region preferred by recent experiments. In section II, we describe the method used for exploring the parameter space. We analyse scenarios with light neutralinos in the MSSM assuming different priors in section III while the results for the NMSSM are presented in section IV.

II. METHOD

To efficiently explore the multi-dimensional parameter space, we have performed a Markov Chain Monte Carlo analysis (based on the Metropolis-Hastings algorithm). We have used micrOMEGAs2.4 [33, 34] to compute all observables. This code relies in turn on SuSpect [35] for calculating the particle spectrum in the MSSM and on NMSSMTools [36] for calculating the particle spectrum and the various collider and B-physics constraints in the NMSSM.

We use the method of burn-in chains, i.e. we first explore the parameter space till we find a point with a non-vanishing likelihood. When such a point is found, we continue the chains, keeping all the points that are retained by the MCMC. However, since it is difficult and time-consuming to find a good starting point, we require to speed up the process that the likelihood times the prior (hereafter referred to as $Q$) associated with the starting point exceeds the value $Q > 10^{-12}$, and use an exponential prior on $m_{\chi}^2$ to make sure that the starting point is within close proximity of the low neutralino mass region. However, when this point is found, we replace the exponential prior on $m_{\chi}^2$ by a flat prior. Since low mass neutralinos are quite unlikely with respect to heavier ones (and since finding them also requires a certain amount of fine-tuning), we have decided to perform two independent scans. One aims at exploring the mass region ranging from 0 to 50 GeV (to include the preferred region of the two WIMP recoil-like events reported by CDMS-II). A proper exploration of the parameter space is obtained after generating approximately 50 chains of $10^7$ points each.

The total likelihood function for each point is the product of the likelihood functions evaluating the goodness-of-fit to all the data set that are displayed in Table I. These include B physics observables, the anomalous magnetic moment of the muon, $(g-2)_\mu$, the Higgs and sparticles masses obtained from LEP and the corrections to the $\rho$ parameter. For the MSSM case, only LEP mass limits on new particles were taken as a sharp discriminating criterion with $L = 0$ or 1. Other criteria had some tolerance. For the NMSSM limits, on the Higgs sector, on the $Z$ partial width and on neutralino production as computed by NMSSMTools were also taken as a sharp discriminating criterion.

We use a Gaussian distribution for all observables with a preferred value $\mu \pm \sigma$,

$$F_2(x, \mu, \sigma) = e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

and

$$F_3(x, \mu, \sigma) = \frac{1}{1 + e^{-\frac{x-\mu}{\sigma}}},$$

for observables which only have lower or upper bounds. The tolerance, $\sigma$, is negative (positive) when one deals with an upper (lower) bound.

| constraint | value/range | tolerance | applied |
|------------|-------------|-----------|---------|
| S-masses   | -           | none      | both    |
| $\Omega_{\text{WMAP}} h^2$ | 0.01131 - 0.1131 | 0.0034 | both |
| $(g-2)_\mu$ | $25.5 \times 10^{-10}$ | stat: $6.3 \times 10^{-10}$ | sys: $4.9 \times 10^{-10}$ | both |
| $m_{h}$ | $\leq 114.4$ | 1% | MSSM |
| $Z \rightarrow \chi_1 \chi_1$ | $\leq 1.7$ MeV | 0.3 MeV | MSSM |
| $e^+ e^- \rightarrow \chi_{12,3}$ | $\leq 0.1$ pb | $0.001$ pb | MSSM |
| $\Delta M_s$ | $117.0 \times 10^{-13}$ GeV | th: $21.1 \times 10^{-13}$ GeV | exp: $0.8 \times 10^{-13}$ GeV | NMSSM |
| $\Delta M_d$ | $3.337 \times 10^{-13}$ GeV | th: $1.251 \times 10^{-13}$ GeV | exp: $0.033 \times 10^{-13}$ GeV | NMSSM |

Finally we also require that the neutralino relic density satisfies

$$100\% \Omega_{\text{WMAP}} h^2 > \Omega_{\chi} h^2 > 10\% \Omega_{\text{WMAP}} h^2,$$

with $\Omega_{\text{WMAP}} h^2 = 0.1131 \pm 0.0034$ [41]. The cases where $\Omega_{\chi} < \Omega_{\text{WMAP}}$ should correspond to scenarios in which there is either another (if not several) type of dark matter particles in the galactic halo [42] or a modification of gravity (cf e.g. [43]). In case of a multi component dark matter scenario, there could be either very light e.g. [44][47] or very heavy particles (including very heavy neutralinos), depending on the findings of direct detection experiments.

III. MSSM SCENARIOS

In what follows, we consider the MSSM with input parameters defined at the weak scale. We assume minimal flavour violation and equality of the soft masses between sfermion generations. We further assume a common mass $m_{\tilde{q}}$ for all sleptons, and for all squarks $m_{\tilde{q}}$ (but we have checked that we...
found consistent results by relaxing this universality assumption. We allow for only one non-zero trilinear coupling, \( A_t \). The gaugino masses \( M_1 \) and \( M_2 \) are free parameters which, in particular, allows to have \( M_1 \ll M_2 \) implying a light neutralino much below the EW scale. The parameter \( M_2 \) satisfies the usual universality condition in GUT scale model, that is \( M_2 = 3M_1 \). The Higgs bilinear term, \( \mu \), the ratio of Higgs vev’s, \( \tan \beta \) and the pseudoscalar mass \( M_A \) are also free parameters.

This MSSM-EWSB model with only eight parameters can reproduce the salient features of neutralino dark matter. Indeed, apart from the mass of the LSP, the most important parameters are the gaugino/higgsino content of the LSP, determined by \( \mu \) and \( M_1, M_2, \tan \beta \), as well as the mass of the pseudoscalar which can enhance significantly neutralino annihilations into fermion pairs.

### A. Neutralino masses smaller than 15 GeV

To sample the low neutralino mass range, we take our priors in the range

\[
\begin{align*}
M_1 & \in [1, 100] \text{GeV} & M_2 & \in [100, 2000] \text{GeV} \\
\mu & \in [0.5, 1000] \text{GeV} & \tan \beta & \in [1, 75] \\
m_L & \in [100, 2000] \text{GeV} & m_\tilde{q} & \in [300, 2000] \text{GeV} \\
A_t & \in [-3000, 3000] \text{GeV} & M_A & \in [100, 10000] \text{GeV}
\end{align*}
\]

We consider separately the cases \( \mu > 0 \) and \( \mu < 0 \). The results of our MCMC simulations for \( \mu > 0 \) are displayed in Fig. [1] and [2].

Fig. [1] represents \( Q/Q_{\text{max}} \), the weight normalized to the best weight, with respect to the free parameters that we have considered. The first plot shows that the bino mass is peaked around \( M_1 \in [15, 19] \text{GeV} \) while the second plot shows that \( \mu \) is below 150 GeV. That is, it is near the lower bound that satisfies the LEP limits on charginos. Thus, the LSP is dominantly bino-like with a small Higgsino component.

The third and fourth plots in Fig. [1] show that \( \tan \beta \) is very large (\( \tan \beta \in [40, 60] \)) and \( m_A \) is relatively small (\( m_A \in [120, 170] \text{GeV} \)). This basically indicates that the main neutralino pair annihilation proceeds through the s-channel exchange of a light pseudo-scalar Higgs boson. The results also show that the sleptons and squarks are preferably heavy (\( m_L \in [500, 1200] \text{GeV} \) and \( m_\tilde{q} \in [0.8, 2] \text{TeV} \)).

In Fig. [2] we display the same quantity but with respect to the neutralino mass. As one can see, the preferred value for the neutralino mass \( m_\tilde{\chi}_L \) lies in between 13 and 15 GeV. We found no scenario where the neutralino mass would be smaller than 10 GeV.

In Fig. [3] we display the (spin-independent) elastic scattering cross-section \( \sigma^{SI}_\chi \) times the fraction of neutralino in the halo \( \xi \) versus the neutralino mass and the limits from CDMS and XENON 100. Here (and in the following), we have assumed values for the quarks coefficients in the nucleon (defined by setting \( \sigma_{n\nu} = 45 \text{MeV} \), \( \sigma_0 = 40 \text{MeV} \) in micrOMEGAs [48]) that lead to rather low cross-sections in order to be conservative in our predictions. Since there are uncertainties on the escape velocity and scintillation function of XENON 100, we also performed a rescaling of \( L_{\text{eff}} \) with the energy (see [49]) and kept a conservative energy-dependent value for \( L_{\text{eff}} \). In principle, this should enable us to derive the most conservative limit as possible.

Since all the light candidates that we have found lie within the excluded region (which is defined by both CDMS and XENON 100 exclusion curves), our results strongly suggest light MSSM neutralinos cannot explain neither the CoGeNT nor the DAMA/LIBRA data. Hence, if dark matter is indeed as light as 10 GeV, MSSM neutralinos are extremely unlikely to be a viable explanation.

We reach the same conclusion by using collider constraints. Indeed, since the points that we have found are associated with a light pseudo-scalar Higgs, one can use the 95% exclusion limits from TEVATRON in the MSSM plane of \( \tan \beta \) versus \( m_A \) [50] to constrain the scenarios selected by our MCMC. These collider limits were obtained by studying the MSSM Higgs boson production in association with \( b \) quarks in the \( \pi^+\pi^- \) final states with up to 2.2 fb\(^{-1}\) of data. Two benchmark scenarios were in fact considered to describe the situations of maximum and no mixing in the stop sector [51] for both \( \mu > 0 \) and \( \mu < 0 \).

In Fig. [4] we thus plot the results of our MCMC analysis and superimpose the TEVATRON constraints. We find that, independently of the direct detection constraints, none of the scenarios corresponding to light MSSM neutralinos and \( \mu > 0 \) can survive the TEVATRON constraints on the mass of the pseudo-scalar Higgs. The fact that neutralinos lighter than 15 GeV (\( \mu > 0 \)) are excluded by both direct detection and collider constraints enable us to conclude that MSSM-EWSB neutralinos (in scenarios with \( \mu > 0 \)) must be heavier than 15 GeV.

This argument is actually valid whatever the precise value of the relic density. This is therefore a very strong conclusion. Note that our results are somewhat discrepant with [19]. This may originate from the fact that Ref. [19] did not take into account the latest constraint on \( B_s \rightarrow \mu \mu \). Indeed, we do obtain many more points at low mass if we disregard this constraint, as was also pointed out in Ref. [50]. However, all these “new” points are also excluded by the TEVATRON limits.

We have performed a similar analysis for the case \( \mu < 0 \). However, we found that it is extremely difficult to obtain a good starting point. Besides the total Likelihood of the points retained by the MCMC is much smaller than that for \( \mu > 0 \), this is mainly due to the \( \langle g-2 \rangle \mu \) constraint and to a lesser extend to the constraints from B-physics. Hence, MSSM-EWSB neutralinos lighter than 15 GeV are also ruled out in the case \( \mu < 0 \).

Of course our lower bound on \( \Omega_{\chi} h^2 \) (see Eq. [5]) is arbitrary. One could consider an even smaller fraction of light neutralino.

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1. The elastic scattering cross-section can be up to one order of magnitude larger for other choices of the quark coefficients.
2. In Ref. [52] it was shown that the \( \langle g-2 \rangle \mu \) constraint could be avoided if one takes opposite signs for gaugino masses with both \( \mu < 0 \) and \( M_2 < 0 \). We have not considered this class of scenarios.
FIG. 1: MSSM-EWSB scenario for $\mu > 0$ and $m_\chi < 15$ GeV. These plots represent the rescaled weight $Q/Q_{\text{max}}$ of the points selected by the MCMC versus the free parameters that we have considered. Curves in dark blue correspond to points with a likelihood greater than 99.4%; curves in blue correspond to points with likelihood greater than 95.4% and smaller than 99.4% of the maximum Likelihood and points in pale blue are all the remaining points having a likelihood greater than 68%.

FIG. 2: $Q/Q_{\text{max}}$ with respect to the neutralino mass in MSSM-EWSB scenario for $\mu > 0$ and $m_\chi < 15$ GeV. We use the same color code as in Fig. 1.

FIG. 3: MSSM-EWSB scenario with $\mu > 0$ and $m_\chi < 15$ GeV. Spin-independent cross section on proton times the fraction of neutralinos in the Milky Way dark halo ($\xi$) versus the neutralino mass $m_\chi$. The dark red (light pink) points have a likelihood greater than 99.4% (68%).

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FIG. 4: Distribution of the points selected by our MCMC analysis in the \( \tan \beta - m_A \) plane in the MSSM-EWSB scenario with \( \mu > 0 \) and \( m_{\chi} < 15 \) GeV. The TEVATRON limits are displayed for the case of no-mixing (dash) or maximum mixing (full) in the stop sector, same color code as in Fig. 3.

B. Neutralino masses less than 50 GeV

Given our conclusion concerning light neutralinos, it is interesting to derive the lower limit for the neutralino mass in the MSSM. For this, we focus on scenarios where the neutralino mass ranges from 1 to 50 GeV.

FIG. 5: Same as in Fig. 4 for the MSSM-EWSB scenario with \( \mu > 0 \) and \( m_{\chi} < 50 \) GeV.

The distribution of \( Q/Q_{\text{max}} \) for the free parameters of the model are summarized in Fig. 5. As one can see, the preferred value of the neutralino mass lies in the [28,50] GeV range and is similar to the value of \( M_1 \) which lies in [40,50] GeV. Since \( M_1 < \mu \), such neutralinos are mostly bino-like. Nevertheless some higgsino component is necessary for efficient neutralino annihilation through Z or light Higgs exchange, hence the preference for small values of \( \mu \). As compared to the previous case, the pseudoscalar Higgs is no longer necessary to provide efficient annihilation, and therefore \( m_A \) moves towards higher values. Furthermore \( \tan \beta \) varies in a wider range since the \( B \)-physics constraints are relaxed at large values of \( m_A \).

In Fig. 6 we display the points selected by the MCMC in the plane \( (m_A, \tan \beta) \) where we have superimposed the TEVATRON constraints. Interestingly enough, at low values of the mass of the pseudo-scalar Higgs \( m_A < 300 \) GeV, there are two separate regions of \( \tan \beta \). One is peaked around 10-20 while the second lies between 50-70. Typically when the pseudoscalar is light, constraints on \( B \)-physics decrease the value of the likelihood especially when \( \tan \beta \) is large. However as we have seen previously the new channel for neutralino annihilation through a pseudoscalar exchange leads to an acceptable relic density and to a good global likelihood when \( \tan \beta > 50 \). Note that, even though very large values of \( \tan \beta \) do not appear plausible, they do indicate the type of regions that lead to a neutralino mass in the [1,50] GeV range.

The spin-independent cross section versus the neutralino mass is displayed in Fig. 7. The scenarios where the neutralino mass is greater than 28 GeV survive both the TEVATRON and Direct Detection limits. Although such a value is likely to be irrelevant to explain CoGeNT data, it might be important in light of the two CDMS “events”.

FIG. 6: Distribution of the points selected by our MCMC analysis in the \( \tan \beta - m_A \) plane in the MSSM-EWSB scenario with \( \mu > 0 \) and \( m_{\chi} < 50 \) GeV. In red, we display the points which are excluded by both TEVATRON, XENON 100 and CDMS. In yellow, we show the points which satisfy TEVATRON and which are excluded by XENON 100 and CDMS and in green, all the points which survive both constraints.

For \( \mu < 0 \), we again found that the Likelihood of the points is much smaller than for \( \mu > 0 \), owing mainly to the \( (g-2)\mu \) constraint which disfavours large values of \( \tan \beta \) as well as low values of \( M_2 \) and \( m_{\tilde{t}} \) [15].

IV. NMSSM SCENARIOS

The Next-to-Minimal Supersymmetric Standard Model (NMSSM) is a simple extension of the MSSM that provides a solution to the naturalness problem. This is achieved by
the introduction of a gauge singlet superfield, denoted by $S$. The VEV of this singlet determines the effective parameter $\mu = \lambda \langle S \rangle$ which is then naturally of the EW scale [53]. The part of the superpotential involving Higgs fields reads

$$W = \lambda S H_u H_d + \frac{1}{3} KS^3$$

and the soft Lagrangian

$$\mathcal{L}_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2$$

$$+ (\lambda a_1 H_u H_d S + \frac{1}{3} \kappa A_S S^3 + \text{h.c.})$$

The NMSSM contains three neutral scalar fields, $h_1, h_2, h_3$ and two pseudoscalar neutral fields, $a_1, a_2$ as well as a charged Higgs, $H^\pm$. The model also contains five neutralinos, the new field is the singlino, $\tilde{S}$. For a pure state the singlino mass is simply [53]

$$m_\tilde{S} = \frac{2 \kappa \mu}{\lambda}.$$  

After using the minimization conditions of the Higgs potential, the Higgs sector is described by six free parameters, $\mu, \tan \beta$ as well as $\lambda, \kappa, A_\lambda, A_\kappa$. Other free parameters of the model are, as in the MSSM, the soft masses for sfermions, trilinear couplings and gaugino masses.

An important feature of the model is that both the singlino and the singlet fields can be very light and yet escape the LEP bounds. This is because these fields mostly decouple from the SM fields [53]. This opens up the possibility for new annihilation mechanisms for light neutralinos in particular if the LSP possesses an important singlino component. The singlino can annihilate efficiently through the exchange of light singlet Higgses as well as into light Higgs singlets [54].

### A. Neutralino masses smaller than 15 GeV

To explore the parameter space of the NMSSM model that allow for light neutralinos we follow the same procedure as for the MSSM. Our priors lie in the range:

$$M_1 \in [1, 200] \text{GeV} \quad M_2 \in [100, 2000] \text{GeV}$$

$$\mu \in [0, 1000] \text{GeV} \quad \tan \beta \in [0.1, 65]$$

$$\lambda \in [0, 0.75] \quad \kappa \in [0, 0.65]$$

$$A_\lambda \in [-2000, 5000] \text{GeV} \quad A_\kappa \in [-5000, 2000] \text{GeV}$$

$$m_1 \in [100, 2000] \text{GeV} \quad m_3 \in [300, 2000] \text{GeV}$$

$$A_t \in [-3000, 3000] \text{GeV}$$

As before, we assume common soft masses for squarks and sleptons and we keep the gaugino masses $M_1$ and $M_2$ uncorrelated while $M_3 = 3 M_2$.

The distribution of $Q/Q_{\text{max}}$ for the free parameters are displayed in Fig. 8. As in the MSSM the bino mass is peaked below 20 GeV although a long tail extends to 200 GeV. In this tail the LSP is mostly a singlino which mass is determined from Eq. 6. The parameter $\lambda$ that determines the mixing of the singlino to other neutralinos is never very small, so that the singlino does not decouple completely. The preferred values for $\mu \approx 150 - 250$ GeV are higher than in the MSSM. On the one hand LEP2 limits on $e^+ e^- \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_i^0$ or on the light Higgs constrain low values of $\mu$ while a light singlino LSP prefers low values for $\mu$, Eq. 6. The parameter $\kappa << 1$ also favours a light singlino. Intermediate values of $\tan \beta$ are preferred. The parameter $A_\lambda$ that controls the mass of the singlino Higgses is always small to ensure a light scalar/pseudoscalar as required for LSP annihilation while $A_\kappa$ is usually well above 1 TeV. Sleptons are preferably light while squarks are above 1 TeV. The LSP mass ranges from 1-15 GeV with a distribution peaked towards higher masses. This LSP is either mostly bino or mostly singlino with in any case some higgsino component. The most important feature of this scenario is the fact that the Higgs spectrum is constrained: one always predict a light scalar, dominantly singlet, with a mass below 120 GeV (generally below 30 GeV) as well as a pseudoscalar singlet with a mass preferably below 30 GeV, see fig. 10. Note that the value of 30 GeV for the mass corresponds to twice the neutralino mass and is thus just a consequence of the prior on the neutralino mass. Furthermore we find generally that either $m_{\tilde{\chi}_1^0} - m_{\tilde{\nu}_1} / 2 < 1 - 4$ GeV (with a similar mass splitting with $h_1$, cf Fig. [11]) or that $m_{\tilde{\chi}_2^0} > m_{\tilde{\nu}_1}$. This is because the annihilation of the light LSP relies either on pseudoscalar/scalar exchange or on the new light scalar pairs final states. The rest of the Higgs sector consists of MSSM-like doublets with preferred values for the heavy neutral and charged scalars above 2 TeV. Note that we have checked that the recent re-analysis of LEP2 limits on a Higgs decaying into two light pseudo-scalars did not put further constraints on our model parameters [55]. The light LSP scenarios can be classified in three broad classes: 1) a (pure or mixed) singlino LSP annihilating via pseudoscalar/scalar singlet Higgses into fermion final states, for this only a small singlino component of the LSP is neces-
FIG. 8: $Q/Q_{\text{max}}$ for the points selected by the MCMC versus the value of the free parameters that we have considered in the NMSSM for $\mu > 0$ and $m_{\chi} < 15$ GeV, same color code as Fig.1

sary. 2) a bino LSP with small higgsino/singlino components annihilating into a pair of light scalar Higgses or 3) as in the MSSM a bino LSP with some Higgsino component annihilating via Higgs doublets. This channel is more efficient at large values of $\tan\beta$ although the B-physics constraints severely restrict the very large values of $\tan\beta$.

The predictions for the elastic scattering cross section span several orders of magnitude, from $10^{-56}$ to $10^{-38}$ cm$^2$, see Fig.12. The largest cross sections are found in scenarios with a light $h_1$, for example for $\sigma_{SI}^{\chi p} > 10^{-43}$ ($10^{-41}$) cm$^2$ requires $m_{h_1} < 20$ (8) GeV. At first sight this can be a bit surprising since such a light Higgs is dominantly singlet and thus couples very weakly to quarks in the nucleon - recall that the $h_1 q\bar{q}$ coupling is only possible through the doublet component - nevertheless this suppressed coupling is compensated by an enhancement factor due to the small $h_1$ mass in the propagator, $\propto 1/m_{h_1}^2$. In scenarios where the elastic scattering cross-section is large, the LSP is generally dominantly bino (or, in a few cases, a singlino) with a non-negligible higgsino fraction. This means that the doublet $h_2$ also contributes to the spin independent cross section since the LSP coupling to the doublet depends on the Higgsino component of the LSP. The very low cross-sections are found in scenarios where the LSP pair-annihilation benefits from the enhancement of the pseudoscalar exchange in the s-channel near the resonance while the elastic scattering cross-section, which proceeds through scalar exchange in t-channel, does not benefit from a similar enhancement.

Note that in Ref.56 an upper bound on the SI cross-section was obtained by optimizing the contribution of the doublet exchange, we found larger cross sections because we explored regions where the additional contribution of the light singlet was important.

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3 In Ref. [22], light CP-even Higgs exchange was proposed to explain the CoGeNT result with light neutralinos within the BMSSM model.
FIG. 9: $Q/Q_{\text{max}}$ with respect to the neutralino mass in the NMSSM for $\mu > 0$ and $m_{\chi} < 15$ GeV, same color code as in Fig. 1.

FIG. 10: $Q/Q_{\text{max}}$ with respect to the mass of the scalar (left) and pseudoscalar Higgs (right) in the NMSSM for $\mu > 0$ and $m_{\chi} < 15$ GeV, same color code as in Fig. 1.

FIG. 11: NMSSM scenario for $\mu > 0$ and $m_{\chi} < 15$ GeV. Mass difference $m_{\chi} - m_{a_1}$ We use the same color code as in Fig. 1.

We have also explored the region of parameter space which gives neutralino masses up to 50 GeV. As for the MSSM we found many scenarios that satisfies all the constraints. These have a neutralino mass near $M_Z/2$ and a SI cross section below the present limits. Note that we also found that neutralinos lighter than 15 GeV were accompanied by a singlet pseudoscalar having a mass $\approx 2m_{\chi}$. However, these scenarios did not have a significant singlino component. In addition, they had a lower likelihood than in the case of heavier neutralinos.

B. LHC signatures for light neutralino scenarios

Light NMSSM neutralino scenarios ($m_{\chi} < 15$ GeV) can lead to distinctive signatures at colliders both in the Higgs and the neutralino sector. First, the usual dominant decay mode of the light scalar doublet Higgs can be greatly suppressed because of new decay modes into neutralinos $h_2 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ as well as into light Higgses $h_2 \rightarrow h_1 h_1, a_1 a_1$. The light scalar/pseudoscalar are expected to decay predominantly into $b\bar{b}, \tau^+ \tau^-$ or invisibly into $\tilde{\chi}_1^0$. Therefore both the search for the invisible Higgs in the W fusion channel with a signature in two tagged jets and missing $E_T$ and the search for Higgs via $W h_2$ production with $h_2 \rightarrow h_1 h_1 \rightarrow 4j$ [57, 58] are important channels at the LHC.

Distinctive signatures are also expected in the neutralino and chargino sectors. The NLSP, $\tilde{\chi}_2^0$, can contain a small component of singlino and therefore be much lighter than $\tilde{\chi}_1^0$. The favourite discovery channel, $\tilde{\chi}_2^0 \rightarrow ll$ is however much suppressed since the decay modes can involve light Higgs states, $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h_1, \tilde{\chi}_1^0 a_1$, leading to $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 b\bar{b}$ or to the completely invisible decay $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \tilde{\chi}_1^0$. Furthermore the single lepton signature of the chargino will be much suppressed since the decay $\tilde{\chi}_2^+ \rightarrow W^+ \tilde{\chi}_1^0$ is generally accessible because of the large mass splitting with the LSP.
V. CONCLUSION

We have investigated whether light neutralinos in the MSSM and the NMSSM could still be viable candidates and furthermore lead to large values of the elastic scattering cross-section as required to explain recent CDMS, CoGeNT, DAMA/LIBRA data.

In the MSSM, we basically exclude neutralinos lighter than 15 GeV. In order to satisfy the WMAP constraint, these particles must exchange a light pseudoscalar Higgs at large values of tanβ. However, recent TEVATRON results on supersymmetric Higgs searches rule out this possibility. In addition, we found (after imposing all collider and direct detection constraints) that the lower limit on the neutralino mass is about 28 GeV in the MSSM ($\mu > 0$).

In the NMSSM, it is easier to find light neutralinos that satisfy all the constraints. This is generally achieved when the LSP contains a singlino component. One salient feature is that these neutralinos are accompanied by a light pseudoscalar and/or scalar singlet. While the elastic scattering cross-sections are generally much below the reach of current detectors in most scenarios, we found that some points can satisfy all the constraints and yet predict elastic scattering cross-sections in the "CoGeNT" region. This is achieved through the presence of a $O(\text{GeV})$ scalar Higgs. However, we should stress that the light neutralinos typically do not provide as good a fit to the data as the ones around 50 GeV.

NMSSM scenarios with light neutralinos could be further probed with direct detection experiments of increased sensitivity. They also lead to distinctive signatures in Higgs and SUSY particles searches at colliders that could be studied. Finally, indirect signatures of the light neutralino (including synchrotron emission, see Ref. [59]) will be investigated in a future work.

Note added: After submitting this paper, we became aware of another preprint [60] which also finds that light neutralinos in the NMSSM can have large elastic scattering cross sections through the exchange of a light scalar Higgs.

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