Indirect Dark Matter Searches and Models

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Abstract

Indirect dark matter searches are briefly reviewed. Current experimental data from satellites and Cherenkov telescopes searching for antimatter and gamma rays in galactic and extragalactic regions, are compared with predictions from theoretical models of dark matter. The analysis is focused on WIMPs such as the neutralino and the sneutrino, and a superWIMP such as the gravitino, in several interesting supersymmetric models. In particular, the discussion is carried out in the context of $R$-parity conserving models such as the MSSM, the NMSSM, and an extended NMSSM, and the $R$-parity violating model $\mu$SSM.

Keywords: Dark Matter, Indirect Detection, Theoretical Models, Supersymmetry, Neutralino, Sneutrino, Gravitino
1 Introduction

Elucidating the nature of the dark matter (DM) left over from the Big Bang and its possible detection constitutes a key challenge in modern physics [1]. Evidence indicating the presence of DM can be obtained at very different scales: from cosmological ones through the analysis of the angular anisotropies in the cosmic microwave background (CMB) radiation, down to galactic scales considering lensing and galaxy dynamics studies. Although the amount of DM has been determined with huge precision by WMAP through the measurements of the CMB [2],

$$\Omega_{DM} h^2 = 0.1109 \pm 0.0056, \tag{1}$$

its composition is still unknown beyond the fact that it has to be mainly non-baryonic. Since within the standard model of particle physics there are no viable non-baryonic candidates, the existence of DM represents one of the most compelling evidences for physics beyond the standard model [1].

A new particle with the following properties is needed:

i) It must be stable or long-lived, because it must have been produced after the Big Bang and still present today.

ii) It must be neutral, because otherwise it would bind to nuclei and would be excluded from unsuccessful searches for exotic heavy isotopes.

iii) It must reproduced the observed amount of DM (1).

Actually, a particle with weak interactions and a mass of the order of the electroweak scale, the so-called WIMP (Weakly Interacting Massive Particle) [1], is able to fulfill property iii). The reason is that the relic density of WIMPs can be computed with the result

$$\Omega_{WIMP} h^2 \simeq \frac{3 \times 10^{-27} \text{ cm}^3 \text{s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle}, \tag{2}$$

where the denominator is the annihilation cross section of two DM particles averaged over their velocity distribution. Then, if a new particle with weak interactions exists in Nature, its annihilation cross section turns out to be of the right order, $\langle \sigma_{\text{ann}} v \rangle \sim 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$, to reproduce the observed density of the Universe (1).

The forthcoming onset of the large hadron collider (LHC) will provide information about the nature of particle physics at the electroweak scale. The LHC could produce a new kind of particle with a mass of the order of the GeV-TeV that could be in principle a candidate for DM. Such a production and detection would be of course a
great success, but not a complete test of the DM theory. Even if we are able to measure the mass and interactions of the new particle, checking whether the observations are fulfilled (1), we would never be able to test if the candidate is stable on cosmological scales. A complete confirmation can only arise from experiments where the DM particle is detected as part of the galactic halo or extragalactic structures. As we will discuss below, this can come from direct and indirect DM searches. Actually, there has been a impressive progress on this issue in recent years, with significant improvements in the precision and sensitivity of experiments. The combination of LHC data with those provided by direct and indirect searches can be a crucial tool for the identification of the DM. Thus, these three detection strategies are ideal because they allow exploring in a complete way many different particle DM models. Not only that, in the case of a redundant detection (in two or more different experiments) the combination of their data can provide good insight into the nature of the DM, maybe even allowing its identification.

The DM could be detected directly in underground laboratories through its elastic interaction with nuclei inside detectors. Actually, there are claims about DM signals by direct detection experiments such as DAMA/LIBRA [3], CoGeNT [4], and CRESST [5]. These claims seem to be consistent with a low-mass particle, possibly of about 10 GeV. However, other experiments like CDMS [6], XENON [7] and SIMPLE [8] do not confirm this result. Thus the situation is controversial.

In this work we will concentrate on indirect DM searches. These are carried out in neutrino and Cherenkov telescopes, and satellites, through the analysis of the DM annihilation or decay products in the Sun, galactic center, galactic halo or extragalactic structures. Such products can be neutrinos, gamma rays and antimatter. In the next sections we will review the current experimental situation concerning indirect searches of WIMPs through gamma rays and antimatter. Actually, claims by several authors about detection, using Fermi satellite data from the galactic center and galaxy clusters, have also appeared recently in the literature [9, 10]. As for the case of direct detection signals, the situation is also controversial. As we will discuss below, there is no confirmation of detection by the Fermi collaboration or by other authors analyzing the data. We will also review the comparison between the experimental data and the predictions from theoretical models containing WIMPs. Although the zoo of DM candidates is huge [1], we will concentrate on supersymmetric candidates such as the neutralino [1] and the sneutrino [11]. Finally, we will discuss that the gravitino is an interesting (superWIMP) candidate for DM in R-parity breaking models, and can in
principle be detected through its decay products, such as gamma rays.

The paper is organized as follows. In Section 2 we will discuss four interesting supersymmetric models where the neutralino, sneutrino and gravitino are candidates for DM. In Section 3 we will review indirect WIMP searches through antimatter and gamma rays, and the implications for the theoretical models containing neutralinos and sneutrinos. We will discuss how the DM is searched in the galactic halo, galactic center, dwarf spheroidal galaxies and clusters of galaxies. We will also comment recent claims about possible DM detection in the galactic center and the Virgo cluster. In Section 4 a similar analysis will be carried out for superWIMP searches through gamma rays, focusing on gravitino DM in $R$-parity breaking models.

2 Models

Supersymmetry (SUSY) is one of the most attractive theories for physics beyond the standard model, and actually, one of the main goals of the LHC is to find its signatures. As mentioned in the Introduction, SUSY candidates for DM exist and we will discuss them in the context of four interesting SUSY models.

2.1 MSSM

The Minimal Supersymmetric Standard Model (MSSM) is the most popular SUSY extension of the standard model. It has been studied in great detail in the literature, and it is the simplest extension: no extra fields are included apart from the SUSY partners of the standard model fields. In addition to the Yukawa couplings for quarks and charged leptons, the MSSM superpotential contains the so-called $\mu$-term involving the Higgs doublet superfields, $\hat{H}_1$ and $\hat{H}_2$,

$$W = \epsilon_{ab} \mu \hat{H}_1^a \hat{H}_2^b ,$$

where $a, b$ are $SU(2)$ indices. The presence of the $\mu$-term is essential to avoid the appearance of an unacceptable Goldstone boson associated to a global $U(1)$ symmetry. It is also necessary to generate chargino masses, and present experimental bounds imply that $\mu$ must be larger than about 100 GeV.

On the other hand, the MSSM superpotential conserves a discrete symmetry called $R$-parity (+1 for particles and -1 for superpartners), and therefore SUSY particles are
produced or destroyed only in pairs. As a consequence, the lightest supersymmetric particle (LSP) is absolutely stable, and therefore fulfills property \( i) \) described in the Introduction. This implies that the LSP is a possible candidate for DM. It is remarkable that in interesting regions of the parameter space of the MSSM the LSP is the lightest neutralino, a physical superposition of the Bino, and neutral Wino and Higgsinos. The neutralino is obviously an electrically neutral particle, fulfilling therefore property \( ii) \). It is also a WIMP, fulfilling property \( iii) \). Thus, in the MSSM, the lightest neutralino is a very good DM candidate [1]. Let us finally remark that the fact that the LSP is stable, and typically neutral, implies that a major signature in accelerator experiments for \( R \)-parity conserving models is represented by events with missing energy.

The phenomenological analysis of the MSSM can be carried out in two frameworks. One of them consists of defining the soft SUSY-breaking terms at the grand unification scale, \( M_{GUT} \), and through the renormalization group equations (RGEs) to study the low-energy theory. If the soft terms are assumed for simplicity universal at \( M_{GUT} \), the model is usually called the Constrained Minimal Supersymmetric Standard Model (CMSSM). Another possibility is to define the parameters of the MSSM directly at the electroweak scale, without any constraint from the RGEs. In this case the model is usually called the effective MSSM (effMSSM).

Unfortunately, the \( \mu \)-term introduces a naturalness problem in the theory, the so-called \( \mu \) problem [12]. Note to this respect that the \( \mu \)-term is purely SUSY, and therefore the natural scale of \( \mu \) would be \( M_{GUT} \) or \( M_{Planck} \). Thus, any complete explanation of the electroweak scale must justify the origin of \( \mu \), i.e. why its value is of order \( M_W \) and not \( M_{GUT} \) or \( M_{Planck} \). There are very interesting solutions to this problem that necessarily introduce new structure beyond the MSSM at low energies. Several of these solutions, and the associated SUSY models, are discussed below.

### 2.2 NMSSM

The Next-to-Minimal Supersymmetric Standard Model (NMSSM) provides an elegant solution to the \( \mu \) problem of the MSSM via the introduction of a singlet superfield \( \hat{S} \) under the standard model gauge group. Substituting now the \( \mu \)-term in (3) by

\[
W = \epsilon_{ab} \lambda \hat{S} \hat{H}_1^a \hat{H}_2^b + k \hat{S} \hat{S} \hat{S},
\]

when the scalar component of the superfield \( \hat{S} \), denoted by \( S \), acquires a vacuum expectation value (VEV) of order the SUSY breaking scale, an effective interaction
\( \mu \hat{H}_1 \hat{H}_2 \) is generated through the first term in (4), with \( \mu \equiv \lambda \langle S \rangle \). This effective coupling is naturally of order the electroweak scale if the SUSY breaking scale is not too large compared with \( M_W \). In fact, the NMSSM is the simplest SUSY extension of the standard model in which the electroweak scale exclusively originates from the SUSY breaking scale. The second term in (4) is allowed by all symmetries, and avoids, as the \( \mu \)-term in the MSSM, the presence of a Goldstone boson.

Due to the presence of the superfield \( \hat{S} \), in addition to the MSSM fields, the NMSSM contains an extra CP-even and CP-odd neutral Higgs bosons, as well as one additional neutralino. These new fields mix with the corresponding MSSM ones, giving rise to a richer and more complex phenomenology. For example, the results concerning the possible detection of neutralino DM turn out to be modified with respect to those of the MSSM in some regions of the parameter space.

### 2.3 An extended NMSSM

An interesting extension of the NMSSM can help us to explain the origin of neutrino masses. Since experiments induce us to introduce right-handed neutrino superfields, \( \hat{\nu}_c \), in the superpotential (4), this can be extended with [13]:

\[
\delta W = \epsilon_{ab} Y_{ij}^{i} \hat{H}_2^b \hat{L}_i^a \hat{\nu}_c^j + \kappa_{ij} \hat{S} \hat{\nu}_c^i \hat{\nu}_c^j ,
\]

where \( i, j \) are generation indices. Here Majorana masses for right-handed neutrinos of the order of the electroweak scale are generated dynamically through the VEV of the singlet \( S \), \( M_\nu = \kappa \langle S \rangle \). This is an example of a seesaw at the electroweak scale. Light masses are then obtained with a value \( m_\nu = Y_{e}^2 v_2^2 / M_\nu \), which implies Yukawa couplings \( Y_e \) of the order \( 10^{-6} \), i.e. of the same order than the electron Yukawa.

The left-handed sneutrino in the MSSM, even if it is the LSP, is not a viable DM candidate. Given its sizable coupling to the \( Z \) boson, left-handed sneutrinos either annihilate too rapidly, resulting in a very small relic abundance, or give rise to a large scattering cross section and are excluded by direct DM searches.

However, in this model a purely right-handed sneutrino can be a viable candidate for DM [11]. Through the direct coupling to the singlet, the sneutrino cannot only be thermal relic DM reproducing the WMAP result (1), but also have a large enough scattering cross section with nuclei to detect it.
2.4 \( \mu \nu \) SSM

As mentioned above, experiments induce us to introduce gauge-singlet neutrino superfields. Then, given the fact that sneutrinos are allowed to get VEVs, we may wonder why not to use terms of the type \( \tilde{\nu}^c \tilde{H}_1 \tilde{H}_2 \) to produce an effective \( \mu \) term. This would allow us to solve the \( \mu \) problem of the MSSM, without having to introduce an extra singlet superfield as in case of the NMSSM. This is the basic idea of the so-called ‘\( \mu \) from \( \nu \)’ Supersymmetric Standard Model (\( \mu \nu \) SSM) [14, 15]: natural particle content without \( \mu \) problem.

In addition to the MSSM Yukawa couplings for quarks and charged leptons, the \( \mu \nu \) SSM superpotential contains:

\[
W = \epsilon_{ab} Y^i_{\nu} \tilde{H}_2^b \tilde{L}_i^a \tilde{\nu}_j^c + \epsilon_{ab} \lambda^i \tilde{\nu}_i^c \tilde{H}_1^a \tilde{H}_2^b + \kappa^{ijk} \tilde{\nu}_i^c \tilde{\nu}_j^c \tilde{\nu}_k^c.
\]  

When the scalar components of the superfields \( \tilde{\nu}_i^c \), denoted by \( \tilde{\nu}_i^c \), acquire VEVs of order the electroweak scale, an effective interaction \( \mu \tilde{H}_1 \tilde{H}_2 \) is generated through the second term in (6), with \( \mu \equiv \lambda^i \langle \tilde{\nu}_i^c \rangle \). The third type of terms in (6) is allowed by all symmetries, and avoids the presence of a Goldstone boson associated to a global \( U(1) \) symmetry, similarly to the case of the NMSSM. In addition, it contributes to generate effective Majorana masses for neutrinos at the electroweak scale \( \kappa \langle \tilde{\nu}_i^c \rangle \). Thus, the \( \mu \nu \) SSM solves the \( \mu \) problem and explains the origin of neutrino masses by simply introducing right-handed neutrinos.

The above terms in the superpotential produce the explicit breaking of \( R \)-parity (and lepton number) in this model. The size of the breaking can be easily understood if we realize that in the limit where neutrino Yukawa couplings \( Y_{\nu} \) are vanishing, the \( \tilde{\nu}_i^c \) are ordinary singlet superfields like the \( \tilde{S} \) of the NMSSM (5), without any connection with neutrinos, and this model would be like the NMSSM (with three singlets), where \( R \)-parity is conserved. Once we switch on the \( Y_{\nu} \), the \( \tilde{\nu}_i^c \) become right-handed neutrinos, and, as a consequence, \( R \)-parity is broken. This breaking has to be small because of the electroweak scale seesaw implying small values for \( Y_{\nu} \sim 10^{-6} \).

Since \( R \)-parity is broken, this means that the phenomenology of the \( \mu \nu \) SSM is going to be very different from the one of the MSSM/NMSSM. Needless to mention, the LSP is no longer stable, and therefore the neutralino or the sneutrino, having very short lifetimes, are no longer viable candidates for DM.

On the other hand, let us suppose that the gravitino is the LSP. Since it has an interaction term in the Supergravity Lagrangian with the photon and the photino,
and the latter and the left-handed neutrinos are mixed due to the breaking of $R$-parity, the gravitino will be able to decay into a photon and a neutrino. The decay is supressed both by the gravitational interaction (Planck mass) and by the small $R$-parity violating coupling, thus the lifetime of the gravitino can be much longer than the age of the Universe, fulfilling condition $i)$. Additionally, adjusting the reheating temperature one can reproduce the correct relic density (1) for each possible value of the gravitino mass (see e.g. [16] and references therein). Thus condition $iii)$ can also be fulfilled. As a conclusion, the gravitino, which can be classified as a superWIMP given its extremely weak interactions, is an interesting decaying DM candidate in $R$-parity violating models [17].

Since the gravitino decays producing a monochromatic photon with an energy half of the gravitino mass, the prospects for detecting these $\gamma$ rays in satellite experiments can be very interesting, as we will discuss in Section 4.

3 Indirect WIMP Searches

There are promising methods for the indirect detection of WIMPs by looking for evidence of their annihilations through anomalous cosmic rays (CRs) produced in the galactic center, galactic halo or extragalactic structures such as dwarf spheroidal galaxies and clusters [18]. These annihilations will produce $\gamma$ rays or antimatter, and fluxes of these particles can be measured in space-based detectors such as Fermi-LAT ($\gamma$ rays) and PAMELA or AMS (antimatter). $\gamma$ rays can also be measured in Cherenkov telescopes such as MAGIC, HESS or VERITAS. Besides, neutrino telescopes might detect WIMPs passing through the Sun and/or Earth. They may be slowed below escape velocity by elastic scattering. Then, the annihilation of WIMPs accumulated due to gravitational effects produces energetic neutrinos that can be detected in underground (Super-Kamiokande), underwater (ANTARES) and under-ice (IceCube) experiments. In the following we will concentrate on satellite detectors and Cherenkov telescopes.

3.1 Antimatter

The observation of an excess of antiparticles with respect to the astrophysical background, could then be a signature of DM annihilations. Actually, PAMELA has measured the positron fraction, $e^+/(e^+ + e^-)$, up to 100 GeV, obtaining an excess of
positrons that increases with energy above 10 GeV [19]. Recently, Fermi [20] has found that the positron fraction increases with energy between 20 and 200 GeV, consistent with results reported by PAMELA. However, there are several problems with a DM explanation for this large flux. First of all, an excess of antiprotons should have also been observed, but this was not the case. Besides, PAMELA data would imply $\sigma_{\text{ann}} v \sim 10^{-23}$ cm$^3$ s$^{-1}$, but, following (2), this means that the value of $\Omega_{DM}h^2$ is much smaller than 0.1. To avoid this problem one would have to require boost factors provided by clumpiness in the DM distribution ranging between $10^2$ and $10^4$. However, the high-energy positrons mainly come from a region within few kpc from the Sun (those far away lose their energies during the propagation), where boost factors larger than 10 are not expected. On the other hand, astrophysical explanations for this excess are possible. For example, contributions to the fluxes of positrons from pulsars or CRs interacting with giant molecular clouds [18, 21].

3.2 $\gamma$ rays

An excess of $\gamma$ rays with respect to the astrophysical background could also be a signature of DM particle annihilations. As will be discussed below, searches for this excess can be carried out in different regions of the Milky Way or in extragalactic objects.

3.2.1 Intermediate galactic latitudes

The diffuse galactic $\gamma$-ray emission (DGE) is produced by CRs, mainly protons and electrons, interacting with the interstellar gas, via $\pi^0$-production and bremsstrahlung, and radiation field, via inverse Compton (IC) scattering. Measurements by the EGRET satellite, which covers the energy range 30 MeV to 30 GeV, indicated an excess of $\gamma$-ray emission $\geq 1$ GeV in all directions on the sky [22]. DM explanations were proposed to solve this discrepancy. However, 5-month measurements for energies 100 MeV to 10 GeV and intermediate galactic latitudes, $10^\circ \leq |b| \leq 20^\circ$, reported by Fermi-LAT, which is conducting an all-sky $\gamma$-ray survey in the 20 MeV to $> 300$ GeV energy range, show no excess [23]. Fig. 1 from [23] compares the LAT spectrum with the spectra of an $a\ priori$ DGE model, and a point source contribution and unidentified background (UIB) component derived from fitting the LAT data. Overall, the agreement between the LAT-measured spectrum and the model shows that fundamental processes are consistent with the data.
Figure 1: LAT data of diffuse emission intensity averaged over all galactic longitudes for latitude range $10^\circ \leq |b| \leq 20^\circ$ compared with model, source, and UIB components. Model (lines): $\pi^0$-decay, red; bremsstrahlung, magenta; IC, green. Shaded/hatched regions: UIB, grey/solid; source, blue/hatched; total (model + UIB + source), black/hatched. Figure from [23].

3.2.2 Galactic center

Another interesting possibility is to search for the DM particles in the galactic center, since it is expected to contain the largest density of DM within the Milky Way. A preliminary analysis of the Fermi-LAT observations of the galactic center was reported in [24]. The bulk of the $\gamma$-ray emission from that region was explained with the detected sources and the DGE model. Nevertheless, an unmodeled excess was present about 2–5 GeV. The conclusion was that any attempt to disentangle a potential DM signal will require deep understanding of the conventional astrophysics background. An excess might be due to other astrophysical sources (for instance unresolved point sources). Analyses within the Fermi collaboration are still under-way, and no further publications have appeared.

On the other hand, utilizing three years of data from Fermi-LAT, it has been claimed that the spectrum of the $\gamma$-ray emission from the galactic center shows evidence of a spatially extended component which peaks at energies between 300 MeV and 10
GeV [9], and that if interpreted as DM annihilations products, the DM particles with the correct relic density (1) should have a mass in the range of 7–12 GeV (if annihilating dominantly to leptons) or 25–45 GeV (if annihilating dominantly to hadronic final states). Note that the former of the above mass ranges is consistent with signals reported by the direct detection experiments DAMA/LIBRA, CoGeNT, and CRESST.

Let us finally remark that this result seems to be consistent with a cuspy density profile \( \rho(r) \sim r^{-1.25} \) to \( r^{-1.40} \). Although this kind of profiles are not obtained in dark-matter-only simulations, where a NFW density profile is typically obtained with a behavior \( \rho(r) \sim r^{-1} \), it is worth noticing that when baryons are included in the analysis of the inner galactic region, the compression effect turns out to be important and can produce \( \rho(r) \sim r^{-1.45} \), implying large \( \gamma \)-ray fluxes [25].

However, as mentioned above when discussing Fermi-LAT observations of the galactic center, a potential problem of the result obtained in [9] is that the conventional astrophysics background in the galactic center is not well understood. In particular, it has been claimed that this emission might be consistent with a millisecond pulsar population in the central stellar cluster [26] or with CR effects [27]. Also, in ref. [28], using a different spectrum of the point source at the galactic center assumed by [9], no DM particles are needed to explain the data.

To constrain particle physics models, one can compare the observations with the theoretical computation of the flux. The observed differential flux at the Earth coming from a direction forming an angle \( \psi \) with respect to the galactic center is

\[
\Phi_\gamma(E_\gamma, \psi) = \frac{1}{2} \frac{\langle \sigma_{\text{ann}} v \rangle}{4\pi m_{\text{DM}}^2} \sum_i \frac{dN_i^{\gamma}}{dE_\gamma} B_i \int_{\text{l.o.s.}} \rho^2 \, dl ,
\]

where the discrete sum is over all DM annihilation channels, \( dN_i^{\gamma}/dE_\gamma \) is the differential \( \gamma \)-ray yield, \( B_i \) is the branching ratio, \( \langle \sigma_{\text{ann}} v \rangle \) is the annihilation cross section averaged over its velocity distribution, \( m_{\text{DM}} \) is the mass of the DM particle, and \( \rho \) is the assumed DM density in the galaxy. The integral is computed along the line of sign (l.o.s.) in the direction \( \psi \). Thus the result is factorized into the 'astrophysical factor' given by the integral which depends on the DM density, and the 'particle physics factor' in front which depends on the DM particle properties.

Recently, neutralino DM in the CMSSM was studied [29] using the above eq. (7) and the current Fermi-LAT data. The conclusion was that the latter are not sensitive to any of the CMSSM scenarios with appropriate relic density studied. This analysis was carried out assuming NFW and Einasto profiles. In [30], a very light
right-handed sneutrino DM in the extended NMSSM discussed in Subsection 2.3, was analyzed. In particular the possible detection of a sneutrino of about 10 GeV, compatible with results by DAMA/LIBRA, CoGeNT and CRESST, through its $\gamma$-ray annihilation product from the galactic center, was discussed in detail. Assuming NFW, Einasto, and isothermal profiles, the conclusion is that the fluxes are too small to be observed. Therefore, without a significant improvement of the understanding of the background, one cannot constrain the relevant parameter space of these models.

3.2.3 Dwarf spheroidal galaxies

Local group dwarf spheroidal galaxies (dSphs) are attractive targets because they are nearby, are largely DM dominated systems, and they are relatively free from $\gamma$-ray emission from other astrophysical sources since have no active star formation or detected gas content. Thus, although their expected number of signal counts is smaller than the one from the galactic center, given that they are further away, dSphs exhibit a favorable signal to noise ratio. However, 11-month measurements of 14 dSphs reported by Fermi-LAT show no significant $\gamma$-ray emission above 100 MeV [31].

To constrain particle physics models, a sample of 8 dSphs without large uncertainties in the DM content was used. For each galaxy the collaboration modeled the DM distribution via a NFW density profile (neglecting boosts due to substructures in order to be conservative). With this information and using eq. (7), upper limits on photon fluxes and on $\langle \sigma_{\text{ann}} v \rangle$ were derived as a function of the WIMP mass, for each dSph and for specific annihilation channels [31] (see also [32]). Concerning the latter, continuum $\gamma$ rays produced by the decay of neutral pions generated in the cascading of annihilation products is the origin of the fluxes. Typical products are quark-antiquark pairs. An interesting case motivated by SUSY DM is a $b\bar{b}$ final state. Another final state motivated by SUSY, with a smaller branching fraction, is $\tau^+\tau^-$. An intermediate case with a mixed $b\bar{b}$ and $\tau^+\tau^-$ in the final state is also very common in SUSY. The resulting integral flux above 100 MeV turns out to be at a level below about $10^{-9}$ photons cm$^2$ s$^{-1}$ Of course, these results apply not only to neutralinos but to any model with this kind of final states.

In Fig. 2 from ref. [31], the LAT sensitivity in the $(\langle \sigma_{\text{ann}} v \rangle, m_{\text{DM}})$ plane is compared with predictions from neutralino DM in the effMSSM. Draco and Ursa Minor dSphs set the best limits. As expected, for neutralinos fulfilling (1), $\langle \sigma_{\text{ann}} v \rangle$ is given by $\sim 3 \times 10^{-26}$ cm$^3$ s$^{-1}$ or by smaller values when coannihilation effects in some regions
Figure 2: effMSSM in the $(\langle \sigma_{\text{ann}} v \rangle, m_{\text{DM}})$ plane. All points are consistent with all accelerator constraints and red points have a neutralino thermal relic abundance consistent with WMAP. Blue points have a lower thermal relic density but it is assumed that neutralinos still comprise all of the DM in virtue of additional non-thermal production processes. The line indicate the Fermi 95% upper limits obtained from likelihood analysis on the 8 selected dwarfs. Figure from [31].

No excess has been observed either from dSphs in Cherenkov telescopes like HESS, VERITAS, MAGIC and Whipple, implying limits from these studies that vary between a few times $\sim 10^{-23}$ to a few times $10^{-22}$ cm$^3$ s$^{-1}$ for a 1 TeV mass neutralino. Let us remark that Cherenkov telescopes are more sensitive to DM particles with high masses (higher than about 200 GeV), and their searches are thus complementary to those of Fermi.

In a recent work [33], using 24 months of data, adding Segue 1 and Carina to the sample of 8 dSphs analyzed in [31], and including the uncertainty in the DM distribution, Fermi-LAT collaboration was able to obtain stronger constrains combining all the dSph observations into a single joint likelihood function. The upper limits on the annihilation cross section can be seen in Fig. 3 from ref. [33]. Thus WIMPs with thermal cross sections are ruled out up to a mass of about 27 GeV for the $b\bar{b}$ channel.
and up to a mass of about 37 GeV for the $\tau^+\tau^-$ channel.

### 3.2.4 Clusters of galaxies

Nearby clusters of galaxies are also attractive targets. They are more distant (the flux decreases with the cluster distance $D$ like $1/D^2$), but more massive than dSphs. Like dSphs, they are very DM dominated. Besides, they typically lie at high galactic latitudes where the contamination from galactic $\gamma$-ray background emission is low. However, 11-month measurements of the 6 galaxy clusters, AWM 7, Fornax, M49, NGC 4636, Centaurus, and Coma, reported by Fermi-LAT show no excess [34]. Assuming a NFW profile for the DM density distribution of the clusters, the Fermi collaboration have explored the implications of the non-detection of DM in terms of constraints on particle models, such as e.g. neutralino DM in the effMSSM. In general, they turn out to be weaker than those found for dSphs. Although they improve significantly the constraints obtained from observations of Coma and Perseus clusters by HESS and MAGIC, respectively.

Recently, 8 galaxy clusters assuming a NFW profile were also analyzed in [35], based on 3 years of Fermi-LAT data. Depending on the DM mass, annihilation cross sections down to $5 \times 10^{-25}$ cm$^3$ s$^{-1}$ can be constrained. When DM substructures down to the
Earth mass, $10^{-6}M_\odot$, are present, these limits could improve possibly going down to the thermal cross section of $3 \times 10^{-26}$ cm$^3$ s$^{-1}$ for DM masses $\leq 150$ GeV and annihilation into $b\bar{b}$. In most cases the combined limits are at the level of the strongest individual limit, unlike the case of dSphs where they can improve the cross-section limits a factor of several for a wide range of DM masses.

A similar conclusion was obtained in [36], where 49 galaxy clusters were analyzed. They showed that the stacking analysis only improve the cross-section limits by about 10% at tens of GeV mass regime, and at most by a factor of $\sim 2$ at multiple mass regime. On the other hand, in [36] a special attention to modeling DM with baryonic compression was paid. Although substructure boost was also included in the analysis, the authors attacked this issue in a conservative way, emphasizing that the consideration of Earth-size DM halo requires extrapolation of the subhalo mass function by 12 orders of magnitude, since present numerical simulations can resolve halos of only about $5 \times 10^7 M_\odot$. They concluded that the substructure boost could exceed the contraction boost, only if the minimum subhalo mass is considerably smaller than one solar mass. Otherwise, it can be neglected with respect to the contraction effect. The authors decided to concentrate the analysis on the Fornax cluster, which found to be the most promising one yielding the largest annihilation signal. This is because of its proximity to the Earth (20 Mpc) and its relatively large mass ($\sim 10^{14} h^{-1} M_\odot$), also because it does not host any bright active galactic nuclei unlike the Virgo cluster (that host M87), and finally because it has regular thermal gas profiles and a spherical central massive elliptical galaxy, NGC 1399, making the calculation of compression based on the assumption of spherical symmetry reasonable. The result was that the annihilation signatures are boosted by a factor of 4 due to the compression. Thus for DM mass of about 10 GeV, the upper limit, $10^{-25}$ cm$^3$ s$^{-1}$, was obtained.

Unlike above analyses of galaxy clusters, in [10] evidence for extended $\gamma$-ray emission from the Virgo, Coma, and Fornax clusters based on 3 years of Fermi-LAT data was reported. When interpreted as annihilation DM particles the data are reproduced with a particle mass in the range 20–60 GeV annihilating into the $b\bar{b}$ channel, or in the range 2–10 GeV and $> 1$ TeV annihilating into $\mu^+\mu^-$. These results seem to be consistent with those obtained in [9] for the galactic center. The significance found is $4.4$, $2.3$ and $2.1\sigma$ for Virgo, Coma and Fornax, respectively, and NFW profiles with substructures were used. However, recently, Bloom representing the Fermi-LAT collaboration [37] also obtained null results using Fermi data, as previous analyses [35, 36].
4 Indirect SuperWIMP Searches

The gravitino as the LSP in $R$-parity violating models was first studied [17] adding the following bilinear terms in the superpotential of the MSSM: $\mu^i L_i H_2$. Then, the detection of gravitino DM through its $\gamma$-ray decay products has been studied in the literature [17, 38]. As mentioned in the Introduction, unlike other $R$-parity violating models which do not try to address the $\mu$ problem (actually in the bilinear model the problem is augmented with the three new bilinear terms $\mu^i$), the $\mu\nu$SSM solves it and accounts for light neutrino masses. Thus it seems to be important to know its predictions concerning gravitino DM detection.

In recent works [16, 39], gravitino DM and its possible detection in the Fermi satellite when decaying in the galactic halo or extragalactic regions such as the Virgo cluster, were discussed in the context of the $\mu\nu$SSM.

Summarizing, it was found that a gravitino DM with a mass range of 0.6–2 GeV, and with a lifetime range of about $3 \times 10^{27}$–$2 \times 10^{28}$ s would be detectable by the Fermi-LAT with a signal-to-noise ratio larger than 3, in 5 years of observations of the Virgo cluster. On the other hand, gravitino masses larger than about 4 GeV are disfavored in the $\mu\nu$SSM by the non-observation of monochromatic lines in the Fermi-LAT data of the galactic halo. For more details of the computation, where N-body simulations of the nearby extragalactic Universe were used, see the talk by G.A. Gómez-Vargas in these proceedings.

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