WIMP dark matter candidates and searches—current status and future prospects

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Abstract
We review several current aspects of dark matter theory and experiment. We overview the present experimental status, which includes current bounds and recent claims and hints of a possible signal in a wide range of experiments: direct detection in underground laboratories, gamma-ray, cosmic ray, x-ray, neutrino telescopes, and the LHC. We briefly review several possible particle candidates for a weakly interactive massive particle (WIMP) and dark matter that have recently been considered in the literature. We pay particular attention to the lightest neutralino of supersymmetry as it remains the best motivated candidate for dark matter and also shows excellent detection prospects. Finally we briefly review some alternative scenarios that can considerably alter properties and prospects for the detection of dark matter obtained within the standard thermal WIMP paradigm.

Keywords: dark matter, particle physics, WIMP, particle astrophysics, astroparticle physics

(Some figures may appear in colour only in the online journal)
1. Introduction

One of the most important quests of contemporary physics is to understand the nature of dark matter (DM) in the Universe. The long-held paradigm is that most DM is cold (CDM) and is made up of some weakly interacting massive particles (WIMPs). The WIMP solution to the DM problem remains attractive for a number of reasons. Firstly, WIMPs arise naturally in a large number of theoretically well-motivated models. Secondly, for reasonable ranges of WIMP mass and annihilation cross section the relic abundance of DM can be obtained through the robust mechanism of thermal freeze-out, possibly augmented with some other production mechanisms. Lastly, thermal WIMPs represent a promising target for DM experiments because a large fraction of their typical detection rates are within reach of current or planned detectors, making them testable by experiment.

We note that the concept of a WIMP as used in the literature is somewhat ambiguous. In general it encompasses a broad category of hypothetical candidates coming from specific theoretical scenarios, or their classes. In general it includes any non-baryonic massive particle (even with a very tiny mass) that interacts with any interaction that is either weak or sub-weak (e.g. axionic, gravitational). In a more commonly used sense, WIMP refers to a particle with mass in the range from about 2 GeV (the so-called Lee-Weinberg bound) up to some 100 TeV (a rough unitarity bound [2]), whose interactions are set basically by the weak interaction coupling of the standard model, although strongly suppressed, as otherwise one would run into conflict with upper limits on its detection cross section.

In this topical review we will focus on the latter, ‘proper’ WIMP category, and will cover the present status of some of the most popular and robust WIMP candidates and prospects for their detection. To this end we will also briefly survey the current experimental search situation, focusing in particular on several recent claims, or hints, of measuring a DM signal.

The field of dark matter is very broad and remains an arena of intense research both on the theoretical and experimental sides. Its various aspects have been covered in a number of review articles and here we mention but some of them. Observational evidence for dark matter can be found, e.g. in [13, 4]. Many WIMP particle candidates and prospects for their detection have been covered in several papers, starting from the early comprehensive review [5] (which, nearly thirty years later, still remains a very useful classic reference) and more recently in [6–9] and [10] which, although mostly devoted to non-standard WIMPs, like axinos and gravitinos, in the first chapter contains a summary of the current views on WIMPs from a particle physics perspective. References [11, 12] provide a recent succinct update on indirect detection aspects of WIMP searches.

The review is organized as follows. In the remainder of this section we briefly summarize observational arguments for DM. Next, in section 2 we present the case for the WIMP solution to the DM puzzle. We start by outlining some general properties of WIMPs (section 2.1), then discuss its production mechanisms in the early Universe (section 2.2) and finally (section 2.3) comment on several specific WIMP candidates that have recently been discussed in the literature—the purpose of this is to provide a broader perspective on the current speculations about particle candidates for DM. In section 3 we turn to the experimental searches and briefly review the current situation both in direct detection (DD) in underground searches (section 3.1) and (sections 3.2–3.6) in several modes of indirect detection (ID), focusing in particular on some recent claims of DM detection. Finally, in section 3.7, we summarize the searches for DM-like particles at the LHC. We devote section 4 to the arguably most popular WIMP candidate, the lightest neutralino of supersymmetry (SUSY) by reviewing and updating its properties and prospect for detection in light of recent progress in DM searches and also of SUSY searches and Higgs boson discovery at the LHC. While most of the section deals with well known SUSY frameworks and standard assumptions, we conclude it by presenting some recent works on relaxing them and discuss ensuing implications. In section 5 we provide a summary and outlook.

5 The bound was actually derived by more authors. For more references, see [1].
1.1. Evidence for dark matter

Over the last decades observational evidence for the existence of large amounts of DM in the Universe has been steadily mounting, and is now described in several reviews [3, 4]. Here we merely briefly summarize some of the better known arguments.

The first claim about the existence of DM is usually attributed to Zwicky’s original paper on the Coma Cluster [13]. The cluster consists of more than a thousand galaxies. Careful analysis of the movement along their gravitational orbits led to the conclusion that there should be a large amount of non-luminous matter contained in the cluster. Zwicky referred to it as ‘dunkle Materie’ (dark matter) and apparently thought it was just ordinary matter in a non-shining form.

One of the most widely recognized arguments for the existence of DM is based on galaxy rotation curves, i.e. the relation between orbital velocity and radial distance of visible stars or gas from the center of a galaxy. It was first noted in the late 1930s that the outer parts of the M31 disc were moving with unexpectedly high velocities [18], an observation that was then confirmed more than thirty years later [19, 20]. According to these observations the velocities of distant stars in M31 remain roughly constant over a wide range of distances from the center of the galaxy, in contradiction with expectations based on the distribution of visible matter in the galaxy. Similar results were later obtained [21] for various other spiral galaxies.

The existence of DM is also supported by data coming from gravitational lensing. Gravitational lensing, or the bending of light in a strong gravitational field (for a review see, e.g. [22]), is most easily observed when light passes through a very massive and/or dense object, like a galaxy cluster or the central region of a galaxy. Light rays can bend around the object, or lens, leading to a distortion of the image of the light source, as can be seen in figure 1(a). This effect is commonly known as strong lensing. The size and shape of the image can be used to determine the distribution of mass in the lens which can then be compared with the visible mass.

When the lens is not as massive as in the case of strong lensing, or when light travels far from the core of the galaxy or cluster, the effect is much weaker. However, it can still be analyzed even in the case of individual stars. Microlensing effects of this kind were proposed [24, 25] to look for DM in the Milky Way in form of massive compact halo objects (MACHOs), which should cause an occasional brightening of stars from nearby galaxies. This strategy led to an exclusion of MACHOs with masses in the range $0.6 \times 10^{-7} - 15 M_\odot$ as the dominant form of DM in the Galaxy [26].

Perhaps the most spectacular argument for the existence of dark matter in clusters can be found in the bullet cluster. It consists of two clusters of galaxies which have undergone a head-on collision [23]. The hot-gas clouds (observed through their x-ray emission) that contain the majority of the baryonic mass in both clusters have been decelerated in the collision while the movement of the galaxies and the dark matter halos in clusters remained almost intact. Analysis of the gravitational lensing effect shows that the center of mass for both clusters is clearly separated from the gas clouds, as can be seen in figure 1(b). One can thus infer the presence of a large amount of additional mass in both clusters. The bullet cluster is the first known example of a system where the dark matter and the baryonic component have been separated from each other.

Studies of weak gravitational lensing of large scale structures (LSS) provide further evidence for DM. In this context the effect is usually called cosmic shear. It causes systematic distortions of the positions of distant galaxies, though the impact is very subtle ($\sim$0.1%–1%). Tangential shear is usually analyzed in terms of two-point (or even three-point) correlation functions that on the other hand can be related to the DM mass density correlation functions. The latter quantity is a Fourier transform of the matter power spectrum and can be used to determine the matter density (both ordinary and dark) of the Universe; see, e.g. [27].

Last but not least, a crucial role in determining the DM abundance in the Universe is played by studies of cosmic microwave background (CMB) radiation. The CMB radiation seen today originates from the decoupling and recombination epoch. Small inhomogeneities in the distribution of its temperature correspond to fluctuations of the matter density in the early Universe that subsequently gave rise to the observed large structures. The power spectrum of temperature anisotropies (see figure 2(a)) when expanded in terms of spherical harmonics depends on cosmological parameters can then be obtained by fitting the resulting spectrum, with some underlying assumption of cosmological model, e.g. the ΛCDM model.

The current values [28] of the relic abundance, that is the ratio of the density to the critical density, of baryonic matter $\Omega_b$, and the corresponding quantity for the non-baryonic DM component, $\Omega_{DM}$ that were obtained by WMAP and more recently by PLANCK by fitting the six-parameter ΛCDM model are:

$$\Omega_b h^2 = 0.022 \pm 0.002$$

$$\Omega_{DM} h^2 = 0.1186 \pm 0.002$$

where $h = H_0 / 100$ km Mpc $s = 0.678(9)$ [28] is the reduced Hubble constant, with $H_0$ denoting the Hubble constant today.

The remaining dominant contribution, $\Omega_\Lambda \approx 0.692$, accounts for the so-called dark energy (for a recent review see, e.g. [30, 31]). A schematic cartoon showing different contributions to the mass-energy content of the Universe is shown in figure 2(b).

Further information about the amount of matter and dark energy components of the Universe can be derived from analyses of baryon acoustic oscillations (BAO, periodic fluctuations in the density of baryonic matter that originated from the opposite effects of gravitational attraction and radiation pressure), supernovae type Ia, or from the Lyman-α forests (neutral hydrogen clouds seen in absorption in quasar spectra). In the case of elliptical galaxies and galaxy clusters another important piece of evidence for the existence of DM comes

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6 Earlier speculations were made by Kapteyn [14], Oort [15] and Jeans [16]. For a historical development, see [17].
from the x-ray emission from hot gas (for further discussion see, e.g. [4]).

2. WIMPs as dark matter

2.1. General properties

One clear conclusion about DM that one can draw from observational evidence is that DM is made up of some particles should be electrically neutral. DM should interact with ordinary matter preferably only weakly (or sub-weakly), where weak can be taken to mean interacting via the weak nuclear force or just having a (sub)weak but non negligible coupling to the standard model particles.

Dark matter self-interactions cannot be too strong in order to be compatible with constraints on structure formation and observations of galaxy cluster systems such as the bullet cluster with current limits of order $\sigma/v < 0.7 \text{cm}^2/\text{g}$ [36]. Note, however, that this limit can be satisfied even for strongly interacting dark matter (SIMP) with $\alpha_x \sim 1$ in the dark sector and the correct relic density obtained thanks to DM mass-dependent $3 \to 2$ processes [37]. Moreover, to be in agreement with CMB data, most of the DM should be non-baryonic in nature.

It has been suggested that DM could be made up of primordial black holes (PBHs) [38] which, if formed before the period of big bang nucleosynthesis (BBN) would not violate determinations of ordinary matter abundance, thus weakening the argument for the need of non-baryonic DM today. The idea of PBHs as DM has recently been revived with a suggestion that the first detection of gravitational waves by LIGO [39] could be potentially explained in terms of two coalescing PBHs [40]. However, there are many limits on PBHs as DM; see [41, 42].

One simple classification of DM particles is based on how relativistic they are around the time when they fall out of thermal equilibrium in the early Universe, i.e. when they decouple from thermal plasma. Hot dark matter (HDM) in
the mass range of up to a few tens of eV, which was still relativistic at the time of decoupling, due to large mean free path did not cluster to form clumps as small as galaxies, and does it reproduce the observed Universe in numerical simulations of LSS formation (see, e.g. [43]). It is incompatible with data from the LSS [44–46] and deep-field observations [47, 48], which constrain the allowed average velocity of the DM particles from above. For these reasons, HDM can only contribute a small fraction, determined by the properties of the CMB, of the total DM density. A familiar (and known to exist) example of possible HDM is neutrinos with a tiny mass.

In contrast, cold dark matter (CDM) behaves very differently. Non-baryonic CDM decoupled from thermal plasma at freeze-out and its density perturbations started growing linearly at the onset of the epoch of matter dominance. This provided early potential wells (seeds), thus triggering and catalyzing the growth of the density perturbations of baryonic matter after it decoupled from radiation some time later. This is the basic reason why CDM generally proves successful in reproducing observations in numerical simulations of LSS, despite well known problems with potentially predicting too few substructures (missing satellites problem) [49, 50] or too dense regions towards the center of the largest DM subhalos obtained in simulations when comparing to the brightest observed dwarf satellite galaxies (too-big-to-fail problem) [51, 52] (for recent review see, e.g. [53]). Cold DM, as opposed to warm or hot DM is also preferred by the properties of the CMB.

Warm dark matter (WDM), in the mass range of a few keV, is a possible form of DM which is intermediate between HDM and CDM. It was still relativistic at the time of decoupling but fluctuations corresponding to sufficiently large halos would not be damped by free streaming. It has been considered as a possible way of ameliorating some apparent problems of CDM, because it reduces the power spectrum on small scales, thus reducing the missing satellite problem of CDM [54] although this has been disputed. It has been claimed, however, that WDM leads to some other problems [55]: the cutoff in the power spectrum $P(k)$ at large wavenumber $k$ implied by WDM will also inhibit the formation of small dark matter halos at high redshift. But such small halos are presumably where the first stars form, which produce metals rather uniformly throughout the early Universe as indicated by observations of the Lyman-alpha forests. An almost sterile neutrino with the mass of a few keV is a popular candidate for WDM. One has to note, though, that such sterile neutrinos are produced in the early Universe being not in thermal equilibrium, hence their effect on the structure formation needs to be studied in detail before drawing robust conclusions (for a recent review see [56]).

An array of these and related arguments have led to establishing a popular (and sensible) paradigm that the dominant fraction of DM is probably cold and that it should be not only (sub)weakly interacting but also non-relativistic and massive, or in short, it is made up of WIMPs. Finally, the DM particles should be either absolutely stable, or extremely long lived (for instance, a recent analysis finds a lower bound of 160 Gyr [57]). This is as much as we can be fairly confident about the nature of DM.

Non-WIMP DM candidates (for a recent review see [10]) have also been vastly explored in the literature. Among them one can distinguish an ultralight axion that emerges from the solution to the strong CP problem. Axion DM can closely resemble CDM when axions, upon thermalization, form a Bose–Einstein condensate with the energy density determined by the mechanism of bosonic coherent motions. Another interesting scenario is to consider extremely weakly interacting massive particles (EWIMPs) as DM candidates. Such weak interactions can naturally appear, e.g. if they are described by non-renormalizable operators suppressed by some high energy scale, e.g. the Planck mass, $M_P ≈ 10^{18}$ GeV, as it is in the case of gravitino DM [58–63] or the Peccei–Quinn scale, $f_a ≈ 10^{11–12}$ GeV, for the axino DM [64, 65].

2.2. Production mechanisms

One property of CDM that is now very precisely established is its cosmological relic abundance—compare equation (1.2)—and the fact that it has been derived from the properties of CMB at the time of recombination or from baryonic acoustic oscillations at the earlier time after (dark) matter dominance started suggest that DM was indeed produced in the early Universe. Big bang nucleosynthesis also place limits on the production of DM from decays during the BBN epoch [66–68]. It is generally assumed that the bulk of dark matter in the Universe was produced between the end of inflation (actually, reheating) and some time before BBN.

Several mechanisms for generating sufficient amounts of DM in the early Universe have been identified and will be briefly reviewed below.

2.2.1. DM production from freeze-out. The most robust mechanism for generating the WIMP DM relic abundance is the so-called freeze-out mechanism. In the very early and hot Universe SM species and DM were in thermal equilibrium, with DM particle production from annihilations balancing each other out. As the Universe expanded and cooled, WIMPs eventually froze out of equilibrium with the thermal plasma. This decoupling happened when the WIMP annihilation rate became roughly less than the expansion rate of the Universe $\Gamma_{\text{ann}} \lesssim H \sim T_f^2 / M_P$, where $T_f$ stands for the freeze-out temperature (the index $f$ indicates that quantities are evaluated at the freeze-out time) and $M_P$ is the reduced Planck mass. After freeze-out the WIMP yield, $Y_\chi = n_\chi / s$, where $n_\chi$ (denoting here generic WIMPs with the symbol $\chi$) is the number density of DM particles and $s \sim T_f^3$ is the entropy density, remained mostly constant.

Given the annihilation rate, $\Gamma_{\text{ann}} = n_\chi \left( \sigma_{\text{ann}} v \right)$, one can rewrite the formula for today’s value of the DM relic abundance in terms of the thermally averaged product of annihilation cross section $\sigma_{\text{ann}}$ and the Moeller velocity, $v_{\text{Mol}} = \sqrt{(\vec{v}_1 - \vec{v}_2)^2 - (\vec{v}_1 \times \vec{v}_2)^2}$, at freeze-out [69],
\[ \Omega_\chi h^2 \simeq \frac{m_\chi n_\chi (T_0)}{\rho_c} h^2 = \frac{T_0^2}{\rho_c} \frac{x_f}{M_P} \frac{1}{(\sigma_{\text{ann}} v_{\text{Møller}})/f}, \]  
(2.1)

where \( T_0 \approx 2.35 \times 10^{-13} \text{ GeV} \) [70] is the temperature of the Universe at present, \( \rho_c \approx 8 \times 10^{-47} \text{ h}^2 \text{ GeV}^{-2} \) [70] is the critical energy density, \( x = m_\chi / T \) and \( \bar{v}_1,2 \) are the velocities of both annihilating DM particles. Note that Møller velocity is equal to the relative velocity of two DM particles, \( |\bar{v}_1 - \bar{v}_2| \) in the center-of-mass frame.

The value of \( x_f \) can be roughly estimated by assuming that around freeze-out the number density of WIMP DM is equal to the non-relativistic equilibrium number density \( n_x \approx n_{xeq} \approx g_x (m_x T / 2\pi)^{3/2} \exp(-m_x / T) \), where \( g_x \) is the number of degrees of freedom for the DM particles. Using \( \Omega_\chi h^2 \approx 0.12 \) one then obtains

\[ x_f^{3/2} e^{-x_f} \approx \frac{10^{-8} \text{ GeV}}{m_\chi}, \]  
(2.2)

This leads to \( x_f \approx 30 \) for \( m_\chi \approx 100 \text{ GeV} - 10 \text{ TeV} \). More careful analysis shows that the appropriate value is closer to \( x_f \approx 25 \) [71].

Finally we put the estimated value of \( x_f \) back into equation (2.1) and find

\[ \langle \sigma_{\text{ann}} v \rangle / f \approx 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}, \]  
(2.3)

for which the correct value of the WIMP DM relic density is obtained (see [72] for a more detailed study). For typical velocities \( v \approx 0.1 \text{ c} \) one obtains a cross section of weak strength for WIMP with mass around the electroweak scale. In the early days, this coincidence was found so remarkable that it was coined as the ‘WIMP miracle’.

However, subsequent developments showed that the situation may well be much more complex. A critique of the ‘WIMP miracle’ can be found in [10]. Here we merely mention that in specific well motivated cases the relic abundance can often be different from 0.12 by several orders of magnitude. For instance, for the neutralino DM of SUSY one typically finds \( \Omega, h^2 \) well in excess of the correct value, as will be discussed in section 4. It is also important to note that WIMP DM particle mass is not necessarily confined to the electroweak scale. An argument based on unitarity gives a generous upper bound on thermal relic mass of the order of 100 TeV [2]. Furthermore, on dimensional grounds, and for simplicity assuming that WIMP mass \( m_\chi \) is the only relevant scale, one expects

\[ \sigma_{\text{ann}} \propto \frac{g^4}{m_\chi^2}, \]  
(2.4)

where \( g \) is a coupling constant responsible for the WIMP annihilation process. One can see that equation (2.3) can be then satisfied for a wide range of masses (from 10 MeV to 10 TeV) and a wide range of coupling constant values (from gravitational to strong) as long as their ratio is kept fixed [10, 73]. Even more freedom can be achieved in a more realistic scenario in which DM-SM mediator mass and its coupling constants to the SM appear in the annihilation cross section.

In a precise treatment, which takes into account the dynamics of freeze-out, the DM yield after freeze-out is found by solving the respective set of Boltzmann equations\(^8\):

\[ \frac{d\rho_R}{dt} = -4H \rho_R + \langle \sigma_{\text{ann}} v \rangle \langle E \rangle (n_\chi^2 - n_{\chi,eq}^2), \]  
(2.5)

\[ \frac{dn_\chi}{dt} = -3H n_\chi - \langle \sigma_{\text{ann}} v \rangle (n_\chi^2 - n_{\chi,eq}^2), \]  
(2.6)

where \( \rho_R \) is the radiation energy density and \( \langle E \rangle \) is the average energy of annihilating DM particles. As can be deduced from equation (2.6) (and even more evidently from a simplified solution (2.1)), the larger is \( \langle \sigma_{\text{ann}} v_{\text{Møller}} \rangle \) at freeze-out the longer WIMPs \( \chi \) stay in thermal equilibrium and therefore the lower relic abundance \( \Omega_\chi h^2 \) one obtains.

One should mention here the related thermal mechanism of coannihilation [75]. If there is some other particle \( \chi' \) in thermal equilibrium, nearly degenerate in mass with the DM WIMP \( \chi \), and such that it annihilates with \( \chi \) more efficiently than \( \chi \) with itself, then it is the mechanism of coannihilation that primarily determines the relic density of dark matter. A more detailed discussion of coannihilation is postponed to section 4.2.1, where we apply it to the case of the neutralino of supersymmetry. It is worth mentioning, though, that the mass degeneracy between \( \chi \) and \( \chi' \) can not only lead to the decrease but also to the increase of the final DM relic density. This can happen when \( \chi' \) can freeze-out before decaying completely into the DM particles, with a larger yield than that of \( \chi \), and subsequently decay to \( \chi \).

2.2.2. Other WIMP production mechanisms. Even though the freeze-out mechanism always contributes to the WIMP DM abundance, in order to be the dominant process a fairly specific range of \( \langle \sigma_{\text{ann}} v_{\text{Møller}} \rangle \) at freeze-out is required. However, several other modes of WIMP production exist which can still lead to the correct \( \Omega_\chi h^2 \) even when this condition is not satisfied. Here we will merely mention some such mechanisms and their specific implementations. A more general and exhaustive discussion can be found in sections IV and V or [10].

First, however, let us mention the situation when \( \langle \sigma_{\text{ann}} v_{\text{Møller}} \rangle \) is too low in which case freeze-out occurs too early and the final relic density of DM may become too large. In such a case the DM relic density must be reduced. This can be achieved by an additional entropy production from out-of-equilibrium decays of some heavy species that occur between the time of the DM freeze-out and BBN which marks the epoch of standard cosmological expansion. In particular such heavy particles could dominate the energy density of the Universe during the period of reheating, i.e. before the radiation dominated (RD) epoch (for a discussion see [1, 76]). If the reheating temperature \( T_R \), i.e. the temperature at which the RD epoch begins, is

\[^8\] One assumes here Majorana DM particles. For Dirac particles there should appear an additional factor of two in the second term on the rhs of equation (2.5). However this plays a negligible role in determining the DM relic density; see, e.g. [74]. In practice one usually neglects the second term on the rhs of equation (2.5), which leads to \( \rho_R \propto t^{-1} \) const, where \( a \) is the scale factor. This condition, along with the Friedmann equation in the radiation dominated epoch, sets the temperature dependence on time when solving equation (2.6).
lower than the DM freeze-out temperature, \( T_f \), the additional entropy production due to, e.g. decays of an inflaton or moduli fields, can effectively dilute away thermally overproduced DM particles. See figure 3(b) and section 4.5.2 for a discussion about neutralino DM.

If \( \langle \sigma_{\text{ann}}\Omega_{\text{DM}} \rangle \) is so low that \( \chi \) particles never reach thermal equilibrium after reheating then they actually never freeze out. In this category of EWIMPs,\(^8\) DM relics can be produced through at least one of two, distinct but not mutually exclusive, mechanisms. Firstly, some heavier particle can first freeze out and then decay into EWIMPs. Note that in this case the resulting number density of DM is still determined at freeze-out. Alternatively, EWIMPs can be produced in scatterings or decays of some heavier particles in the thermal plasma. The production of EWIMPs from decays is most efficient at lower temperatures, \( T \sim m \), just before the Boltzmann suppression kicks in. The production through scatterings is not accompanied by a reverse process which is too inefficient due to low cross sections. In the case of non-renormalizable interactions—typical for gravitinos and axinos—the process is typically more efficient at high temperatures, near the reheating temperature \( T_R \). When interactions are renormalizable, scatterings continuously contribute to the DM relic density until the temperature drops down below a certain value. This has recently been advocated under the name of so-called freeze-in mechanism [78], as the final yield increases with \( \langle \sigma_{\text{ann}}\Omega_{\text{DM}} \rangle \). Note, however, that, strictly speaking, freeze-in is not a new mechanism of DM production but simply refers to a certain type of particle physics interactions that is responsible for generating DM.

Both mechanisms are different from the standard picture based on freeze-out, and both can be efficient, depending on some other quantities (e.g. the DM particle mass or the reheating temperature \( T_R \)). This greatly relaxes the standard thermal WIMP paradigm, as has been shown in the case of axinos [64, 65, 80] (for a recent review see [81]) and gravitinos [59, 62, 63] both of which belong to the class of EWIMPs.

In contrast, if \( \langle \sigma_{\text{ann}}\Omega_{\text{DM}} \rangle \) is larger than the canonical value from equation (2.3), then the thermal yield of WIMPs is too low to produce the DM relic abundance. The DM particles can be additionally produced in late-time decays (after DM freeze-out) of some heavier species. Examples include moduli field (see [82, 83] and references therein), Q-balls (see, e.g. [84]), the inflaton field (see, e.g. [85]) or cosmic strings [86]. Such a non-thermal production of DM is often associated with the aforementioned additional entropy production that also partially reduces the increase of \( \Omega_X h^2 \). As mentioned above, late-time decays can also occur for another species \( \chi' \), almost mass degenerate with the DM particles. In principle, coannihilations reduce both \( Y_\chi \) and \( Y_{\chi'} \). However, it is possible that the yield of \( \chi' \) after freeze-out is larger even than the yield of \( \chi \) calculated in absence of any mass degeneracy. In this case the final DM relic density can be increased with respect to the non-degenerate scenario.

In the (partially) asymmetric DM (ADM) scenario [87, 88] one can accommodate an otherwise too low \( \Omega_X h^2 \) by assuming that one component of the DM relic density from freeze-out is accompanied by one which is set by an initial asymmetry between DM and their antiparticles, in a way analogous to the mechanism of baryogenesis. It is worth noting that, since in the ADM scenario the DM is not its own antiparticle and the abundance of \( \chi \) and \( \bar{\chi} \) particles can be highly asymmetric nowaday, the expected indirect detection rates from \( \chi \bar{\chi} \) annihilations are typically suppressed with respect to, e.g. Majorana DM. A more detailed discussion can be found in, e.g. [89].

Among various other possible ways to deal with too large values of \( \langle \sigma_{\text{ann}}\Omega_{\text{DM}} \rangle \) one should also mention an increased expansion rate of the Universe prior to, and around, the DM freeze-out due to a dynamics of the dark energy content of

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\(^8\)They are also called super-WIMPs [279] or FIMPs [78] (feebly interacting massive particles, although the name of frozen-in massive particles would perhaps be more appropriate [10]) in this case. See also a recent review [79].
Figure 4. Typical ranges of the cross section of DM interactions with ordinary matter as a function of DM mass is shown for some of DM candidates that are strongly motivated by particle physics. The red, pink and blue colors represent HDM, WDM and CDM, respectively. Adapted from [10], Copyright (2014), with permission from Elsevier. [91] (2004) © Indian Academy of Sciences. With permission Springer.

the Universe (see, e.g. [90] for a discussion for quintessence). This leads to an earlier decoupling of the χ particles and therefore larger Ωχh2.

It is clear that the mechanism of freeze-out, while remaining attractive and robust, provides only one of several possible ways of generating WIMP relics in the early Universe. As we shall see later, this will have implications for prospects for DM searches.

2.3. Examples of WIMP candidates

To give a taste of the particle physics context of DM candidates, in this subsection we give examples of some specific WIMPs that either have withstood the test of time, or where there has been some fairly recent activity.

First, to give a wider context, we start with a broad brush picture of different classes of DM candidates that have emerged from particle physics. In figure 4, adapted from [10] (and originally from [91]), we show where different DM candidates lie in terms of their masses and typical detection cross section10. The red, pink and blue colors represent HDM, WDM and CDM, respectively. Both axes span several orders of magnitude making clear that a large range of interaction strengths and masses become allowed by going beyond the thermal WIMP paradigm. Otherwise one would remain confined basically only to the light blue rectangle labeled ‘WIMP’. Such

10 For another broad-range of DM candidates see figure 1 or [92].
In little Higgs models new heavy states are introduced to act as partners of the top quark and gauge bosons, such that the divergences are cancelled at the 1-loop level. To have a DM candidate in little Higgs models there must be a remaining $Z_2$ symmetry often called T-parity [111–113]. The new heavy partner fields are odd under the symmetry while the SM particles are even, this results in lightest partner field being stable. The DM candidate can come in the form of additional scalars which can be charged under SU(2) or a singlet [114, 115]. Alternatively, little Higgs models can have extended gauge sectors with a heavy partner to the photon which can act as a WIMP giving an example of vector DM [112, 116, 117].

The twin Higgs mechanism [118–121] was introduced to solve the unnaturalness problem by positing a twin sector, which is a copy (or partial copy) of the SM related via a $Z_2$ symmetry. The combined Higgs sector posses an approximate $U(4)$ symmetry, and the lightest Higgs then comprises the pseudo-Goldstone boson of the broken $U(4)$. A WIMP DM candidate can arise in twin Higgs models as a member of the twin sector [122] see also [123, 124]. Alternatively the DM can form part of the scalar sector [125] with similar properties to the IDM. The twin DM couples to the standard model via the Higgs leading to a spin-independent scattering cross section that can be searched for with direct detection experiments [122–124]. Annihilation of twin DM can also produce indirect detection signals if it has a sizable annihilation fraction to SM states.

Sneutrinos are an example of a non-thermal WIMP. Sneutrinos are the scalar partners of the neutrinos in SUSY models. For the sneutrinos that were originally proposed as a DM candidate [126, 127] as partners of the SM left handed neutrinos, the spin-independent scattering cross section is generally of weak interaction strength and already firmly ruled out by direct detection experiments unless the sneutrino makes up only a subdominant component of the DM [128–130].

For sneutrino DM to be viable there must be either mixing between the sneutrinos partners of left handed neutrinos and those of the right handed neutrinos [130–134], or lepton violating mass terms that split the sneutrino eigenstates such that elastic scattering via the Z-boson is not possible [129, 135, 136]. Typically purely right-handed sneutrinos have too small coupling to the SM to be a WIMP candidate but may be a viable non-WIMP candidate; see for example [137]. The mixed left-right handed sneutrino DM has recently been reanalyzed in the context of constrained SUSY with updated LHC results in [138].

Models with compactified universal extra dimensions (UED) possess a DM candidate from the tower of Kaluza–Klein (KK) states. In these models SM particles can propagate in the new compactified dimension [139] and particles with quantized momenta in the new spatial dimension appear as heavier copies of the standard model particles and the lightest KK state is stable. The lightest KK state is often a heavy copy of the hypercharge gauge boson and can have the properties of a WIMP [140–143]. Run 1 of the LHC ruled out many of the minimal UED models; see [144, 145] for the status of minimal UED theories post LHC Run 1.

A plethora of other DM candidates exist in the literature and it is clear that it will be up to experiment to identify which of them (if any) is the choice made by Nature. It is also possible to study WIMP DM properties within a framework of generic portals between the dark sector and the SM without specifying other contents of models that are not directly related to DM interactions (see [9] and references therein). Many such possibilities has been explored in the literature including scalar, fermion or vector DM (see, e.g. [146, 147]) with various kinds of mediators that can either belong to the SM, i.e. the Higgs or Z bosons, or can themselves belong to the hidden sector. Such an approach might have less predicting power than well-defined models described above. However, the advantage is that within this framework one can study DM-specific features of many definite models at a time and therefore derive more general conclusions. In particular, it can be checked that Z boson-portal models are already excluded by the current limits with the exception of the case of Majorana DM particles, while for the Higgs boson-portal the only allowed regions for $m_\chi \lesssim 1$ TeV can be obtained for the resonance scenario in which $m_\chi \approx m_\nu/2$ (see a discussion in [9]).

3. Experimental situation

For nearly three decades now the experimental search for DM has continued its intense activity and generally impressive progress that has led to several strongly improved bounds on WIMP interactions. At the same time, with improving sensitivity in some cases new effects have been identified which could be interpreted as caused by DM. We will pay attention to a possible WIMP (or WIMP-like) interpretation of these effects when in this section we make an updated survey of the current situation in several modes of DM searches.

3.1. Direct detection: limits and anomalies

One of the most important strategies to search for WIMP DM is its possible direct detection (DD) through elastic scatterings of DM particles off nuclei [148] (for reviews see, e.g. [149–152]). For WIMPs that interact efficiently enough with baryons this process can lead to a clear signature in low-background underground detectors. In order to distinguish a DM recoil signal from background, today’s detectors typically employ some methods of discrimination (see below). In some cases one looks for the annual modulation of the signal due to the Earth’s movement with respect to the DM halo [153] (for review see [154]). In addition, in the current and the next generation of the DD experiments effort is made to see further DM-specific features in the nuclear recoil energy distribution due to a possible directional detection [155] (for review see [156]).

3.1.1. Formalism. An evaluation of a DM event rate in DD experiments necessarily involves factors from particle physics and nuclear physics, as well as from astrophysics. This can be seen from the formula for the differential recoil event rate\(^{11}\) as a function of the recoil energy $E_r$.

\(^{11}\)Note that for directional detection one needs to consider a double differential rate that takes into account the dependence on the recoil angle (see [156]). Higher order corrections to the differential event rate can be found in [157].
\[
\frac{dR}{dE_r(E_r)} = \left( \frac{\sigma_0}{2\mu^2 m_X} \right) \times F^2(E_r) \times \left( \rho_X \int_{v_{\text{esc}}}^{v_{\text{max}}} d^3v f(v, t) \right).
\]

(3.1)

where \(\sigma_0\) is the DM-nucleus scattering cross section in the zero momentum transfer limit, \(m_X\) is the DM mass, \(\mu \equiv m_X M / (m_X + M)\) is the reduced mass of the WIMP-nucleus system for nucleus of mass \(M\), \(F(E_r)\) is the nuclear form factor of the target nucleus, \(\rho_X\) is the local DM density and \(v\) is the relative velocity of DM particle with respect to the nucleus, while \(f(v, t)\) denotes the distribution of the WIMP velocity with cut-off at the galaxy escape velocity \(v_{\text{esc}}\). The minimum velocity that can result in an event with the recoil energy \(E_r\) is given by \(v_{\text{min}} = (\delta + ME_r/\mu) / \sqrt{2ME_r}\), where \(\delta = 0\) for elastic scatterings.

Since DM WIMPs are characterized by non-relativistic velocities, one typically applies the limit \(v \to 0\) when calculating the cross section. In this case the corresponding cross section can be decomposed into two contributions: the spin-independent (SI) and the spin-dependent (SD), \(\sigma_{\text{SI}}F^2(E_r) \geq \sigma_{\text{SI}}^0 F^2(E_r) + \sigma_{\text{SD}}F^2(E_r)\), where \(\sigma_{\text{SI}}^0\) and \(\sigma_{\text{SD}}\) are given at zero momentum transfer, \(q\), while the dependence on \(q\) is encoded in the form factors. In the absence of isospin violating interactions between DM and nucleons one obtains \(\sigma_{\text{SI}} = \sigma_{\text{SI}}^0 (\mu^2 / \mu_p^2) A^2\) where \(\sigma_{\text{SI}}^0 = (4\mu_p^2 / \pi) f_0^2\) and \(\mu_p\) is the reduced mass of the WIMP-proton system; for a discussion in presence of isospin violation see, e.g. [162]. The limits for the SI cross section are typically presented in the \((m_X, \sigma_{\text{SI}}^0)\) plane. Note the characteristic \(\sim A^2\) dependence (coherent enhancement) that results in an increased differential recoil event rate for heavier target nuclei. The lack of coherent enhancement in SD cross section results in typically lower differential recoil event rates than in the SI case and therefore weaker exclusion limits for \(\sigma_{\text{SD}}^0\) than for \(\sigma_{\text{SI}}^0\). In addition, it is important to note that spin-zero isotopes do not give any signal in DM searches based on SD.

3.1.2. Experiments: limits and anomalies. Scattering of DM particles off nuclei can be detected via subsequently produced light (scintillation photons from excitation and later de-excitation of nuclei), charge (ionization of atoms in a target material) or heat (phonons in crystal detectors). Using one or a combination of two such discrimination techniques is now often employed to disentangle a potential WIMP signal from nuclear recoils and background electron recoils. This is possible due to different quenching factors that describe the difference between the recorded signal and the actually measured recoil energy. The electron recoils constitute the background of the experiment and can come from, e.g. \(\gamma\)-radiation from natural radioactivity or \(\beta\)-decays that take place in the detector surrounding materials, on its surface or even inside the detector. Other sources of background, e.g. neutrons or \(\alpha\)-decays, can be associated with nuclear recoils that can mimic the WIMP signal. Therefore they need to be either screened out or rejected at the level of signal analysis. A particularly challenging type of such a background that will be very important for future detectors, especially for DM mass below 10 GeV, comes from coherent elastic neutrino-nucleus scatterings [163] and cause the existence of the so-called coherent solar neutrino background [164, 165].

Depending on the choice of signal detection technique a variety of target materials can be employed in DD searches. Light signal from DM-nucleus scattering can be collected, e.g. by using scintillating crystals[13]. A well-known example of such a detector is that of the DAMA/LIBRA experiment [167] operating at the LNGS laboratory in Italy, which for two decades have been reporting to see an annually modulated DM-like signal, currently with the significance at the level of 9.3σ [168]. The estimated mass of the DM particles from this measurement would range between 10–15 GeV or between 60–100 GeV depending on the actual nucleus involved in the scattering process (sodium or iodine, respectively). However, the DM interpretation of these results is in strong tension with null results published by some other collaborations: the first XENON1T limit [169], the final LUX [170] and the PandaX-II [171] limits, as well as, in the low mass region, with the limits from CDMSlite [172] and XMASS [173], which excluded the annual modulation of DM interpretation of the effect claimed by DAMA/LIBRA. Non-DM explanations were also considered, including an unknown source of background, as well as possible errors in data collection and processing (for a review see [174]). In addition, other experiments employing similar detection strategy have been proposed to verify the DAMA/LIBRA results. In particular, the results of the KIMS-Csl experiment [175] disfavor interpretation of DAMA/LIBRA signal in which the DM particles scatter off iodine nuclei. This could be circumvented in specific scenarios, e.g. for magnetic inelastic DM (see, however, recent XENON1T limits [176]), in models with dominant WIMP inelastic spin-dependent coupling to protons if different quenching factors are assumed in both experiments [177, 178] (for an extensive discussion see also [92]; for recent limits see [179]) or leptonically interacting DM particles that induce electron recoils [180] (see, however, [181] and references therein).

Charge (ionization) signal from DM-nuclei scatterings can be efficiently measured by low-temperature ultra-low-background germanium detectors [182].[14] This technique has been employed by the CoGeNT Collaboration leading to the claim of an observation of an annually modulated signal in their data [183]. The signal could be consistent with WIMP DM-hypothesis with mass about 7–10 GeV, although it only had 2.8σ significance and it was not confirmed in later searches in the similar mass range. On the other hand, the observed excess of events may be fully explained when an improved background treatment is applied, as pointed out in [184, 185].

[15] Signal in single-phase liquid noble gas detectors also comes entirely from scintillation light emitted by ionized or excited dimers (for a review see [166]).

[14] Another important example of detection technique that focuses on ionization signal from DM-nuclei scatterings is used in gaseous detectors employed in directional dark matter searches (for review see [156]).
The DM interpretation of the CoGeNT data has also been disfavored by other germanium detectors, e.g. CDEX [186] and MALBEK [187]. A halo-independent analysis performed in [188] for light ($\lesssim 10$ GeV) WIMPs showed a strong tension between the DM interpretation of the annual modulation of DAMA/LIBRA and CoGeNT events when compared with the CDMS-Si silicon data.

Phonon signal coming from DM-nuclei scatterings in crystals can provide another important experimental signature in DM DD searches. This technique is particularly useful when looking for low mass DM due to a very good energy threshold. Moreover, one typically further improves the treatment of the background in such experiments by using cryogenic bolometers with additional charge or scintillation light readouts. In 2013 CDMS-Si detector results were published [189] reporting observation of 3 WIMP-candidate events with only 0.19% probability for the background-only hypothesis. The highest likelihood occurred for WIMP-DM with 8.6 GeV mass. However, these results were not confirmed by the germanium CDMS-II [190] and SuperCDMS [191] detectors and there is no plausible DM halo function for which this tension could be alleviated unless one assumes, e.g. exothermic DM with Ge-phobic interactions as discussed in [192].

DM-nuclei scatterings also can be detected via heat signal in experiments based on superheated fluids used as a target material. DM particle passing through a detector can then be visualized thanks to initiated process of bubble creation. Another DM-like signal was found in the data obtained by the CRESST-II Collaboration [193] in 2011. An excess in the expected number of events was observed in two mass ranges around 10 GeV and 25 GeV with the significance at the level of 4.2σ and 4.7σ, respectively. However, as it was pointed out in [194] and confirmed in a later study by the collaboration [195], the excess was mainly due to a missing contribution to the background (see also [92] and [174] for an updated discussion).

The most stringent current limit on $\sigma_p^{SD}$ for large DM mass comes from null results of DM searches in dual phase (liquid-gas) xenon detectors: XENON110 [169]—the most recent (and currently the strongest)—the final LUX result [170] and that of PandaX-II [171], both of which improved the previous limits of XENON100 collaboration [196]; see figure 5. The strongest up-to-date exclusion lines for spin-dependent cross section, $\sigma_p^{SD}$, from DD experiments were published by the PICO collaboration [197, 198] (see also LUX [199] and XENON110 [196] results). However, $\sigma_p^{SD}$ can also be effectively constrained by neutrino telescopes as will be discussed in section 3.5.

A further significant improvement is expected from the currently running XENON1T, later from XENO-Nt [200], LZ [201], and eventually from planned xenon detectors, e.g. DARWIN [202], and for argon as a target material: DEAP3600 [203], ArDM [204] and DarkSide G2 [205]. In the low mass regime large part of the ($m_\chi$, $\sigma_p^{SD}$) parameter space will be
probed by the future germanium and silicon detectors in the SuperCDMS experiment operating at SNOLAB \[206\].

A summary of the above discussion about experimental results is presented in figure 5 where we show current and expected future limits on $\sigma_p^{SI}$ as a function of the DM mass. Anomalies reported in the past by some of the experimental collaborations were not confirmed and are probably due to some non-DM effects that occur either inside or outside the detectors. However, the upcoming years should deliver new data covering regions in the $(m_\chi, \sigma_p^{SI})$ plane well below the current limits and, hopefully, eventually producing a genuine DM signal.

It is important to note that the limits presented in the $(m_\chi, \sigma_p^{SI})$ plane can vary depending on the underlying assumptions about relevant astrophysical quantities, e.g. the local DM density and the DM velocity distribution (see, e.g. \[210\] and references therein). The dependence on the velocity distribution is typically weak \[211\], but can become more important, e.g. if the detector is sensitive only to the tail of the distribution \[212\]. Alternatively, the limits can be shown in a DM halo-independent way \[213\] (see also \[214\] and references therein) if a positive signal is measured by at least two different targets.

### 3.13. Implications for WIMP models.

Direct detection searches play a vital role in constraining various models of WIMP as DM. For instance, early negative results from the Heidelberg-Moscow experiment \[215\] led to an exclusion of the scenario in which the majority of DM was composed of left-handed sneutrinos in the MSSM \[128\], as discussed in section 2.3. Since then many other theoretical candidates have been constrained by null results of searches for the DM particles in DD experiments.

Limits from DD have also been derived on effective contact operators describing possible interactions between DM and the SM particles (for studies related to DD see, e.g. \[158,159\]). One can then translate the usual DD limits shown in the $(m_\chi, \sigma_p^{SI})$ plane into the actual limits on the coefficients of the operators that contribute to $\sigma_p^{SI}$, while the other coefficients remain free and can, e.g. help to achieve the proper value of the DM relic density. Stronger constraints can be obtained when both DD and ID searches are taken into account (see, e.g. \[216\]).

Another phenomenological approach consists in ‘expanding’ the contact operator approach by introducing specific mediators (‘portals’) between the DM sector and the SM particles in a framework of so-called simplified models. For studies related to DD see, e.g. \[217-221\]. It has been pointed out that gauge invariance and perturbative unitarity need to be carefully taken into account when constructing simplified models of DM interactions \[222,223\]. For further discussion about the effective theory approach (EFT) and simplified models see, e.g. \[224\] and references therein.

### 3.2. Gamma rays: limits and galactic center excess

Gamma-rays represent a promising channel in which to search for dark matter (for reviews see, e.g. \[11,12,225\]). WIMPs are expected to annihilate at present leading to the possibility of detecting annihilation products, in particular a spectrum of gamma-rays. Since gamma-rays are not deflected in their journey from the emission point to detection on Earth, the direction of the source can be determined, thus allowing specific targets or regions of DM annihilation to be identified. This can be compared to the situation with charged cosmic rays which are deflected by the magnetic field of the Galaxy. It is therefore possible to use the expected morphology of the DM signal to discriminate it from background \[226\].

#### 3.2.1. Gamma rays from DM.

The spectrum of gamma rays expected from a DM annihilation depends on particles produced in the final state. Typically one assumes that the DM annihilates to standard model particles, which must account for at least some fraction of the annihilations for a WIMP produced through thermal freeze-out. Gamma-ray emission from DM annihilations can be of two types: a continuous spectrum generated by the decay, hadronization and final state radiation of the SM particles produced, and spectral features in the form of gamma ray lines and internal bremsstrahlung.

The continuous spectrum of gamma rays for a specific SM final state can be estimated via Monte Carlo simulation using standard event generators \[227-229\] that include parton showering and hadronization. There is therefore some uncertainty associated with the choice of event generator. Additionally it can also be important to include polarization and electroweak corrections, see \[230\] for a full discussion. Gamma-ray lines appear from the processes $\chi\chi \rightarrow \gamma\gamma$ and $\chi\chi \rightarrow Z\gamma$, since the DM must be electrically neutral these must arise at the loop level but are nearly impossible to mimic by astrophysical background \[231\]. Internal bremsstrahlung can also lead to sharp spectral feature as well as lifting chiral suppression in some models \[232\]. In addition, $\gamma$-rays can also be produced as secondary products of DM annihilations into other particles once the latter interact in interstellar medium, e.g. thanks to inverse Compton scattering (ICS), bremsstrahlung off of galactic gas, neutral pion decays originating from interactions of hadronic cosmic rays with interstellar gas or synchrotron emission induced by propagation in magnetic fields.

#### 3.2.2. Targets for gamma-ray searches.

The morphology of the DM signal can be used to discriminate DM annihilations from the background by focusing searches in regions with a high density of DM. The Galactic Center (GC) is expected to be the brightest source of gamma rays from annihilating DM and has attracted considerable attention as a target for indirect detection experiments \[233\]. The main argument for a high density of DM in the inner regions of galaxies comes from N-body simulations that determine the expected halo distribution (see, e.g. \[234\] and references therein). Dynamical and microlensing observations act to constrain the halo profile \[235\] but there remains significant uncertainty particularly in the GC, see \[236,237\] for some recent determinations. These uncertainties are further compounded by the complex background of conventional astrophysical sources of gamma rays present in the GC \[238\].

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Dwarf spheroidal galaxies (dSphs) in the local group do not suffer from the same problems as the GC of the Milky Way. The dSphs are expected to be DM dominated [239, 240] and are free from the astrophysical backgrounds plaguing the GC. In addition the distribution of DM can be estimated from the dynamics of stars inside the dSphs [241–243]. This makes limits obtained from dSphs more robust, however the expected signal is much lower for a single dSphs than for the GC therefore a stacking analysis is required to obtain competitive limits.

Galaxy clusters are another promising target for gamma-ray searches [244, 245]. The main drawback compared to dSphs is that they suffer from large and poorly understood astrophysical backgrounds, and the expected sensitivity depends strongly on the DM substructure which is unknown.

Finally the full sky can be observed to place limits on annihilations summed over all halos [246]. Since the cosmological DM halos are in general unresolved they contribute to an approximately isotropic background. The isotropic gamma-ray background can be searched for spectral features that would indicate DM annihilations. However, large uncertainties in the backgrounds and expected rate make setting robust limits difficult. A related idea is to measure the angular correlations or cross-correlations to search for a DM signal above the expected isotropic background. Angular correlations can be used to search for extragalactic halos or subhalos as well as other sources such as annihilation of DM around intermediate mass black holes [247]. Cross correlations can also be searched for between the diffuse extragalactic gamma-ray signal and the cosmological DM distribution inferred in other channels such as the CMB and structure surveys (see [248] and references therein).

Figure 6, taken from [249], summarizes the discussion of different targets of gamma-ray observations in terms of the expected signal strength and uncertainty associated with an observed signal or limit. While the strongest case for the observation of DM would be made by complementary observations in several of those channels, two particular targets stand out as currently being most relevant. These are the GC, which has the largest expected signal strength and is therefore the most likely target for a signal to show up first, and combined data from dwarf galaxies of the local group, which currently produce the strongest and most robust limits.

3.2.3. Gamma-ray telescopes. There are two main strategies to observe gamma rays. Since gamma rays interact with the atmosphere direct observation can only be made by space telescopes. On the other hand the ground based telescopes are able to detect gamma rays indirectly by observing the Cherenkov light produced by the showers of charged particles produced by the gamma ray as it hits the atmosphere. Direct observation of gamma rays using space telescopes has been performed by EGRET [250] and the currently running Fermi-LAT [251]. Fermi-LAT uses pair conversion inside a tracking detector, and an electromagnetic calorimeter to determine the energy and incident direction of the gamma-ray. Charged cosmic rays are rejected using an anti-coincidence shield. Fermi-LAT is able to observe gamma rays in the range 20 MeV to 300 GeV and has an effective area of $\sim$1 m$^2$. It typically scans the full sky continuously taking advantage of its large field of view. This means that Fermi-LAT is able to make observations of all of the promising targets for DM annihilation.

The most promising ground based telescopes are the imaging air cherenkov telescopes (IACTs). When a gamma ray enters the atmosphere it interacts creating a shower of secondary particles. The Cherenkov light from the shower is then captured by one or more telescopes on the ground.

One major source of background comes in the form of air showers caused by charged cosmic rays. The cosmic ray background is isotropic and greatly exceeds the gamma-ray signal. This background must be reduced by rejecting showers produced by cosmic rays. This can be done by distinguishing the patterns of Cherenkov light produced by hadronic and gamma-ray showers. Unfortunately, showers produced by electrons cannot be differentiated from gamma rays this way. Monte Carlo simulations [252] are used to model the Cherenkov light from hadronic and gamma-ray showers and to estimate the remaining background for a particular telescope configuration. IACTs have a higher energy threshold than space telescopes since lower energy gamma rays produce less Cherenkov light, however they have the advantage that the volume of atmosphere observed can be large leading to huge (energy dependent) effective area compared to space telescopes. On the other hand, the field of view of IACTs is much smaller and dedicated observations of particular target regions must be made. This means that potential time allowed for DM studies must compete with the other science goals of the IACT. Currently running IACTs include MAGIC [253], VERITAS [254] and HESS [255]. While the next generation telescope will be the currently planned CTA [256].

3.2.4. Current limits and future prospects. We summarize some of the recent limits from Fermi-LAT and the IACTs, as well as future projections in figure 7. On the direct observation side the strongest limits come the stacked analysis of dwarf galaxies [257, 258]. The canonical thermal annihilation rate [72] is shown as a gray dotted line and the current limits

Figure 6. A cartoon, taken from [249], of the relative merits of different gamma-ray observation regions, projected into the expected strength of a signal and relative uncertainties that are associated with the backgrounds and signal strength. Reproduced from [249] with permission.
from Fermi-LAT exclude WIMPs annihilating to $b\bar{b}$ with this cross section below $\sim$100 GeV. The limits from the GC [260, 263] are competitive but are weaker due to the uncertainty in the halo profile. Observations of the Galactic halo [238], galaxy clusters [264] and the Fermi analysis of the intensity [265] and angular power spectrum [266] of IGRB are weaker by about an order of magnitude.

Turning to the current generation of IACTs, figure 7, we first note that the Cherenkov telescopes are sensitive to larger DM masses, whereas Fermi-LAT loses sensitivity as the DM mass increases. The strongest limits come from H.E.S.S. observations of the Galactic Center [259] which at $\sim$1 TeV become stronger than the Fermi-LAT limit. The limits from MAGIC’s observation of the dwarf galaxy Segue 1 [267] and the H.E.S.S. combination analysis of dwarf galaxies [268] are comparable with H.E.S.S. extending the analysis to higher masses. The VERITAS analysis of the Fornax galaxy cluster [269] is the least sensitive and has large uncertainties from the modeling of the substructure and backgrounds (see also recent VERITAS limits from joint analysis of four dSphs [270]). In this search for spectral features the most relevant limits come from Fermi-LAT and H.E.S.S. searches for gamma-ray lines in the GC [271, 272] and galaxy clusters [273].

In the short term, Fermi-LAT, H.E.S.S. and VERITAS are currently taking data, which will continue to place limits on DM annihilation to gamma rays. In particular the best prospects for Fermi-LAT consist of observations of dSphs with more dSphs expected to be discovered in the future (see, e.g. [261]).

Other stringent limits come from possible deviations from a standard recombination history caused by DM-induced cascades of highly energetic particles around this period in the evolution of the Universe [274]. Depending on the actual dominant annihilation final state and on the associated efficiency parameters that describe the fraction of the rest mass energy contributing to CMB distortions, the current limits sometimes reach up to the values of the thermal annihilation cross section around the time of recombination and therefore they are not necessarily directly comparable with the DM ID lines discussed above unless DM annihilation is predominantly of $s$-wave type.

Looking a few years ahead, the CTA experiment [256] is expected to improve on the current limits from H.E.S.S. CTA will be the next very large IACT consisting of arrays in the northern and southern hemisphere, with small, medium and large telescopes giving CTA improved sensitivity over a large energy range from $\sim$100 GeV to tens of TeV [275]. This results in strong expected sensitivity of the CTA to DM annihilations based on observations of the GC [262].

Future gamma-ray space telescopes are planned, e.g. CALET [276], GAMMA-400 [277] and HERD [278]. CALET, recently launched in 2015, has excellent energy resolution above 100 GeV and is likely to place strong limits on gamma-ray lines [276] although will not be competitive with Fermi-LAT for limits on the continuous spectrum of gammarays. The Russian-led GAMMA-400 is in preparation and will

![Figure 7. Limits on the annihilation cross section for the DM particles annihilating into a $b\bar{b}$ pair. Currently the strongest limits correspond to the stacked analysis of dwarf galaxies from Fermi-LAT [257] (solid golden line), combined analysis of both Fermi-LAT and MAGIC [258] (solid black line) collaborations, H.E.S.S. observations of the GC [259] (solid violet line) that we show for the assumed Einasto profile of the DM in the Galactic halo and the Fermi-LAT observations of the inner Galaxy [260] (solid gray line) if the DM distribution is assumed to be consistent with the compressed NFW profile (NFWc). In the low DM mass regime the important limits come from the CMB analysis released by the Planck collaboration [28] which constraints $\sigma v$ around the time of recombination (dashed blue-green line). The future projections are shown for the stacked analysis of 45 dwarf galaxies and 15 years of data taking [261] (dash-dotted brown line), as well as for the CTA collaboration [262] based on the assumed NFW (dashed pink line) and Einasto profiles (dashed red line). The value of the annihilation cross section that corresponds to the thermal production of WIMP DM [72] is denoted with dotted gray line.](image-url)
also mostly contribute to searches for spectral features due to its improved energy resolution compared to Fermi-LAT. The HERD telescope, to be launched in 2020, on the other hand will represent an increase in the effective area and thus should improve on the limits set by Fermi-LAT [278], although detailed studies have not yet been performed.

3.2.5. Galactic Center excess. One of the most intriguing hints of DM detection that has emerged in the last few years is a consistent excess above the expected background observed in the diffuse gamma-rays coming from the GC in the Fermi-LAT data [279, 280]. This signal, known as the galactic center excess (GCE), appears to be peaked around photon energy of a few GeV and was consistently confirmed by many independent analyses (see, e.g. [281–287] and references therein). The Fermi-LAT Collaboration released their own analysis [288] in which GCE is studied employing multiple specialized interstellar emission models (IEMs) that enabled to separate the signal coming from the region surrounding the GC (within ∼1 kpc) from the rest of the Galaxy (see also [289, 290] for related discussion). The excess of gamma rays remained, however its origin is still unclear since the spectral properties of the signal strongly depend on the assumed IEM. In particular, it was pointed out that the photon clustering in the observed excess could be inconsistent with the signal expected from smooth DM distribution [291–293]. Such a possibility has been recently confirmed by the Fermi-LAT collaboration [294]. However, it is also possible that what seems to be a point-like nature of the excess is in fact a result of uncertainties in the background modeling [295]. On the other hand, recent Fermi-LAT analysis of the GCE [296] confirmed the existence of the excess and studied in detail its morphology. In particular, it was shown that the excess is likely to have at least partial astrophysical origin, but the DM interpretation is not excluded. In addition, the excess in the γ-ray signal with a possible DM origin, which is consistent with the GCE, was found in the recent Fermi-LAT study of the center of M31 [297].

The most popular astrophysical explanation is a population of unresolved millisecond pulsars (MSPs) in the GC. The gamma-ray spectrum produced MSPs is known to be compatible with a power law exhibiting an exponential cutoff around 2–3 GeV [298]. It was shown that the GCE can be partly or completely explained by a population of MSPs in the GC [282, 299]. However there is some disagreement as to whether MSPs are really a viable explanation for the GCE based on, e.g. the expected distribution of x-ray binaries [300, 301] (see also [282] for early study in this direction), detailed analysis of the spectra shape of the GCE [302] or distribution of globular clusters [303]. Non-equilibrium processes were also proposed as an explanation for the GCE. In particular, a large injection of CRs into the GC at some point in the past could produce the observed GCE [304–306]. The observed excess can also be associated with X-shaped stellar over-density in the Galactic bulge [307].

As discussed above, it is still possible that DM-induced γ-rays contribute to the GCE. If the GCE is indeed originated from DM annihilations it should then be possible to find their trace in other observation targets or channels. In particular a similar excess can be searched for in the dwarf spheroidal galaxies. Recently the dark energy survey discovered several new dwarf galaxy candidates [308]. In particular, some tentative evidence was proposed for a gamma-ray excess in the direction of nearby Reticulum II [309, 310] and for a faint excess that can come from Tucana III [311], both can be compatible with the GCE. The Fermi collaboration also performed an analysis in which no evidence of an excess was found [312]. Another hint of possible DM discovery was reported in [313] based on the analysis of Fermi-LAT data obtained for nearby galaxy clusters. The observed excess, if interpreted in terms of DM annihilation, can point towards similar mass range for the DM particles as the GCE. However, this requires assuming relatively large boost factors.

Alternatively, one can consider looking for a corresponding excess in the anti-proton spectrum. Comparisons of the GCE and limits from anti-protons were made in [314, 315]. However, the situation is currently unclear with different
analyses claiming that the GCE can be ruled out or is allowed depending on the modeling of the anti-proton propagation (for a recent discussion see, e.g. [316]).

The GCE attracted a great deal of attention also in terms of model building including neutralino DM (see, e.g. [317–324]). Some notable non-SUSY attempts include: multi-step cascade annihilations where the dark matter annihilates to some intermediate states that decay to standard model particles [325–327], approaches based on effective field theory and simplified models of DM [287, 328, 329], Higgs portal models [318, 330, 331], two Higgs doublet models [332, 333], models with a Z′ [334] and vector dark matter models [335].

We summarize our discussion of the GCE in figure 8 taken from [317, 318]. Figure 8(a) shows the residual spectrum for the GCE, as well as various instrumental and astrophysical uncertainties, as discussed in [317]. Initially, fits to the excess favored DM annihilating to bb and τ⁺τ⁻ with mχ ≈ 40 GeV and mχ ≈ 10 GeV, respectively. The annihilation cross section was reported as 2–3 × 10⁻²⁷ cm³ s⁻¹ [285] for bb and 7–9 × 10⁻²⁷ cm³ s⁻¹ for τ⁺τ⁻ [280] final states which are remarkably similar to the annihilation cross section required for a thermal relic. However, these are not the only possible annihilation final states that can fit the GCE signal. Figure 8(b), taken from [318], shows the allowed parameter space for a WIMP annihilating to hh, W⁺W⁻, ZZ, tt and bb for two different Fermi background models. These models favor the lightest and heaviest DM masses. The parameter space between the two fits, indicated by a dashed line, is likely allowed by variation of the background model [318]. Annihilation to lepton final states also still provides a good fit to the GCE where the effect of secondary gamma-rays is important [336].

3.2.6. Other anomalies. Another excess in the Fermi-LAT data from the GC was reported in 2012 by [337, 338]. At that time it was found to be consistent with the γ-ray line around 130 GeV with possible origin from DM annihilations or decays. However, it was soon pointed out that the line was not associated with enough signal in the continuum spectrum which caused some tension with popular DM candidates trying to fit the observed excess, including the lightest neutralino [339, 340]. It has been later shown that the existence of the excess was a statistical fluctuation as its significance has diminished in subsequent improved analyses performed by the Fermi-LAT Collaboration [271].

Interesting features were identified in the spectrum of γ-rays originating from regions around the GC in the WMAP data [341] (so-called WMAP haze), Fermi-LAT data [342, 343] (Fermi bubbles) and Planck data [344] (Planck haze), with a possible common origin. The hard edge-like structures observed for Fermi bubbles disfavor its DM-induced origin. However, it is still possible that some part of the WMAP/Planck haze are not due to the Fermi bubbles and can be better fitted with DM annihilations associated with subsequent microwave synchrotron emission (see, e.g. [345]).

A possible hint of light DM was provided by the excess of γ-rays observed by the INTEGRAL collaboration [346, 347]. It corresponds to 511 keV γ-ray line that has no widely accepted astrophysical explanation. The signal could be compatible with MeV DM annihilating into e⁺e⁻ pairs [348]. Similar signal was found in the direction of Reticulum II, however astrophysical explanations of the excess observed there are favored (for further details see, e.g. [349] and references therein).

The excess in extragalactic radio background found in the ARCADE 2 data [350, 351] could be explained by leptohilic DM with mass typically of order 5–50 GeV [352, 353] that annihilate mostly into electrons and/or muons inducing γ-ray production via subsequent ICS processes. This scenario, however, can already be excluded by the AMS positron data [354]. On the other hand various astrophysical explanations of the observed excess were proposed which, however, also often struggle to accommodate for the whole excess unless numerous faint sources are considered [355] (see, however, [356] for an updated discussion).

3.3. Interlude: WIMP reconstruction from direct detection and gamma rays

Before we proceed with other modes of DM searches, we digress here to consider what information about WIMP properties one could realistically derive in case a real DM signal is actually recorded in either direct detection or in gamma ray experiments, or—even better—in both.

3.3.1. Reconstruction. Once one day a genuine DM signal is observed, we will enter into a new era of reconstructing WIMP properties from experimental data. A number of theoretical studies have already been conducted to test the quality of a putative post-discovery reconstruction in DD experiments depending on the DM mass, respective cross section and target material (for a review see [151]). In particular, it has been pointed out that due to diminishing differences between recoil spectra for a larger DM mass, DD signal analysis can strongly constrain DM properties only for mχ ≤ 100 GeV and for the values of σSI not far below the current limits given the realistic assumptions about achievable exposures. For larger DM mass one typically obtains a σSI/mχ ≈ const degeneracy, as can be seen from equation (3.1) for mχ ≫ M.

However, this can be partially overcome by a possible complementarity between DD and ID searches [357–360], provided of course that a DM-induced signal is found in both types of experiments. We illustrate this in figure 9(a) where we show an interplay between putative signals from XENON1T and from two ID experiments: CTA [256] and Fermi-LAT [251] (for which we assume 15 years of exposure and 46 dSphs). We consider a benchmark point with mχ = 250 GeV and σSI = 5 × 10⁻⁴⁶ cm², as well as the annihilation cross section lying just below the current exclusion bound [258], σSI = 4 × 10⁻²⁶ cm³ s⁻¹ assuming a pure bb final state. As can be seen, an improved mass reconstruction in the ID experiments allows one to strongly constrain σSI which remains unconstrained from above using the XENON1T (and in fact, any DD) data alone.
For a low DM mass a good reconstruction of $m_\chi$ in DD can help interpret the results of ID searches. This is because it is difficult to distinguish among different DM scenarios based on results from ID only, due to an a priori unknown nature of the annihilation final state and the lack of characteristic spectral features for typical final states channels, e.g. $b\bar{b}$ or $\tau^+\tau^-$. However, different annihilation final states that provide a good fit to the same signal observed in ID are often associated with different $m_\chi$ and $\sigma v$. This is, e.g. the case of a well-known Galactic Center excess discussed in section 3.2. Hence, improved DM mass reconstruction in DD experiments could help in better discriminating among various annihilation final states and, eventually, constrain the annihilation cross section.

We illustrate this in figure 9(b) for the benchmark point characterized by $m_\chi = 25$ GeV, $\sigma_p^{SI} = 2 \times 10^{-46}$ cm$^2$, $\sigma_\gamma = 8 \times 10^{-27}$ cm$^2$ s$^{-1}$ and pure $b\bar{b}$ annihilation final state. As can be seen the DM mass reconstruction in Fermi-LAT is limited and it is a consequence of the aforementioned degeneracy in annihilation spectra. On the other hand, a DD measurement of a WIMP signal, which is obviously not sensitive to $\sigma v$, helps to reconstruct $m_\chi$. As a result also the annihilation cross section that fits to the assumed ID signal from the benchmark point is constrained better (for a more detailed discussion see [360]). The reconstructed value of the annihilation cross section could then be mapped into the values of the DM relic density upon additional general assumptions about the WIMP interactions or within the framework of specific models [361].

Figure 9. (a) Comparison of DD (XENON1T) and ID (CTA and Fermi-LAT) experiments in reconstructing the DM properties for the benchmark point with $m_\chi = 250$ GeV and $\sigma_p^{SI} = 5 \times 10^{-46}$ cm$^2$, while the annihilation cross section is equal to $\sigma v = 4 \times 10^{-26}$ cm$^3$ s$^{-1}$ for a pure $b\bar{b}$ final state. The brown region corresponds to 2$\sigma$ reconstructed region for only XENON1T simulated data, the light blue one for Fermi-LAT data (assuming 15 years of exposure and 46 dSphs in the stacked analysis), while the red region was obtained for XENON1T + CTA + Fermi-LAT joint analysis. Similar to (a), but for the benchmark point defined by $m_\chi = 25$ GeV, $\sigma_p^{SI} = 2 \times 10^{-46}$ cm$^2$, $\sigma_\gamma = 8 \times 10^{-27}$ cm$^2$ s$^{-1}$ and pure $b\bar{b}$ annihilation final state. Light blue region corresponds to the the Fermi-LAT reconstruction, while brown one to XENON1T. Combined analysis leads to improved reconstruction of $\sigma v$ as indicated by the red region. Reproduced from [360]. © 2016 IOP Publishing Ltd and Sissa Medialab srl. All rights reserved.

3.4. Cosmic rays: limits and AMS02/Pamela

Charged cosmic rays (CRs) as a tool for DM searches play an important and complementary role to $\gamma$-rays as both are typically produced jointly when the DM particles annihilate or decay (for recent review see, e.g. [12]). The most common types of charged cosmic rays are evidently electrons, $e^+$ and protons, $p$, that can originate from many astrophysical sources [363]. On the other hand, in the case of the annihilations or decays of neutral DM particles, one expects to produce an equal number of both matter and antimatter particles. The latter, including energetic positrons, $e^+$, antiprotons, $\bar{p}$, antideuterons, $\bar{d}$ (see, e.g. [364]), as well as heavier nuclei, e.g. anti-helium [365, 366] are particularly promising tools for DM ID due to relatively low astrophysical background.

3.4.1. Production and propagation. Charged cosmic rays, similarly to photons, can be produced both directly in the annihilation and decay processes as well as in the DM-induced cascades of particles. As a result one obtains a diffuse spectrum of cosmic rays with a cut-off at energies close to $m_\chi$ or $m_\chi/2$ for DM annihilations or decays, respectively. A sharp cut-off can be a ‘smoking-gun’ for DM detection since astrophysical sources are expected to result in a more gradual fall. However, both scenarios can be distinguished only if sufficient amount of data is collected.

Prompt spectra of DM-induced cosmic rays are subsequently modified due to diffusion in the Galactic magnetic field during their propagation to the Earth (for a detailed discussion see, e.g. [225] and references therein). In the case of electrons and positrons one also needs to take into account
various mechanisms of energy-loss, including synchrotron radiation and the inverse Compton scattering on CMB photons or galactic starlight (for a more detailed discussion see [367]). These mechanisms typically play a less important role for antiprotons and antideuterons, since the corresponding terms in the diffusion loss equation are suppressed by the proton or deuteron mass, respectively. However, the spectrum of $p$ and $d$ is affected by their possible interactions with protons in the interstellar medium, as well as by convective Galactic winds that push antiparticles away from the Galactic plane, by diffusive reacceleration and by the solar modulation (see, e.g. [368–370]).

3.4.2. Experiments and anomalies. Searches for charged cosmic rays employ several detection techniques including balloon-type (e.g. HEAT [371], ATIC [372]) and ground-based telescopes (e.g. Pierre Auger Observatory [373], the telescope array [374]), as well as satellite-based experiments including, e.g. PAMELA [375], AMS-02 [376], Fermi-LAT [251].

In particular, in 2009 the PAMELA Collaboration reported an excess in the positron spectrum [377] which was subsequently confirmed by the Fermi-LAT [378] and the AMS-02 [376] experiments. The excess was observed for the energies between $\sim 20$ GeV and $\sim 200$ GeV [379]. The distribution of the high-energy positrons detected by the PAMELA experiment was found to be isotropic [380]. This could be consistent with their DM origin, but can also be explained by astrophysical sources, especially given the uncertain impact of magnetic field configurations on the positron trajectories. Indeed, a DM-related interpretation of the signal was extensively studied both at the level of general WIMPs [381] and within the framework of particular models (see, e.g. [382–386]). As the DM interpretation of the excess typically requires large annihilation cross section and/or boost factors, it was constrained to leptophilic DM models [387, 388] by null results of searches for DM-induced antiprotons of similar strength [389]. However, the leptophilic models themselves seem to be in tension with limits from gamma-ray and x-ray backgrounds [390, 391], the optical depth of the Universe [392, 393], as well as from radio data [394] and the observations of the CMB radiation [28]. The tension is even more pronounced in light of recent limits on $\gamma$-rays discussed in section 3.2. On the other hand, one needs to note that viable astrophysical scenarios were proposed to accommodate for the observed excess (see, e.g. [395]).

Recently an excess in antiproton flux has been confirmed in the AMS-02 data [396] (see, however, [397]). It can be explained by the annihilation of the DM particles with the cross section into hadronic final states of order $3 \times 10^{-26}$ cm$^2$ s$^{-1}$ and the mass that can be compatible with the $\gamma$-ray GCE [398, 399]. On the other hand, it was shown [398] that these AMS-02 results interpreted in terms of upper limits lead to an improvement with respect to the limits from $\gamma$-rays coming from dSphs discussed in section 3.2.

Note that $\gamma$-rays and electron/positron signals cannot be distinguished based on the recorded air shower, but ground-based telescopes are still capable of studying heavier charged CRs, e.g. protons.

All the observed anomalies, as well as other searches for DM-induced charged cosmic rays will be subject to further studies in currently operating or future experiments, e.g. CALET [400], DAMPE [401], GAPS [402], in addition to AMS-02.

3.5. Neutrinos: limits and anomalies

Attempts to discover one elusive particle by capturing another very weakly interacting particle is definitely a very challenging task. However, neutrino detectors proved their unquestionable usefulness as a tool for DM searches thanks to an enormous experimental progress. In particular, current best limits on DM-nuclei spin-dependent cross section $\sigma_{SD}^p$ are based on the results obtained by several neutrino detectors, including ANTARES [403], IceCube [404] and Super-Kamiokande [405].

3.5.1. Neutrinos from DM annihilations. Depending on a particular DM model, neutrinos can be produced mainly in cascades of particles originating from DM annihilations or decays, or even directly in these processes. However, since annihilation or decay rates are typically very small, in order to be able to detect DM-induced neutrinos, one needs to focus on regions in the sky where large concentration of DM particles can be observed, e.g. the Sun, the GC, Galactic halo, nearby galaxies and galaxy clusters or even the Earth.

In particular, DM particles are expected to accumulate inside celestial bodies as their velocity can decrease below the escape velocity due to scatterings off nuclei. Neutrinos are then basically the only products of DM annihilation that can escape and reach detectors. Therefore they can provide a unique DM signature [406]. The expected flux of neutrinos passing through a detector depends on the DM annihilation rate $\Gamma_{\text{ann}}$. For heavy and dense celestial bodies $\Gamma_{\text{ann}}$ is determined by the capture rate of DM $\Gamma_{\text{cap}}$ due to the equilibrium condition $\Gamma_{\text{ann}} \simeq \Gamma_{\text{cap}}$ [407, 408].

When analyzing potential signal from such neutrinos, one needs to take into account both the neutrino spectrum at production and the propagation of neutrinos from the center of the celestial body to the Earth. Both these processes in principle depend on the details of how DM-induced cascades of particles and neutrinos themselves propagate in the dense matter. Needless to mention that proper description of neutrino propagation should also include neutrino oscillations. As a result neutrino fluxes from DM annihilations in the Sun (see, e.g. [410] and references therein) differ from the ones obtained based on spectrum at production outside a dense matter object (see, e.g. [225]).

3.5.2. Experiments and anomalies. Neutrino telescopes (for review see, e.g. [411]) can be divided into two main categories: muon counters (BAKSAN [412]) and water Cherenkov detectors (ANTARES, IceCube, SuperK) [18]. The latter technology

17 In principle one should also take into account the evaporation process of the DM particles from the Sun, but it is negligible for $m_{\chi} \lesssim 4$ GeV [409].
18 Neutrino reactor experiments can also be used to constrain DM properties (see, e.g. recent studies about this in the case of JUNO [413] and KamLAND [414] detectors).
will also be used in planned neutrino telescopes, e.g. BAI-KAL-GVD [415], IceCube-PINGU [416], HyperK [417] and KM3Net [418]. The most important background in searches for DM-induced neutrinos originates from neutrinos produced in scatterings off cosmic rays in the Earth’s atmosphere [419]. On the other hand muons produced in the Earth’s atmosphere can be vetoed more easily in analysis focusing on upward going events. An additional source of background is associated with neutrinos produced in the Sun’s atmosphere [420], though it is expected to be a subdominant contribution [411].

Recently, some interest was raised by an observation of neutrinos with very high energies from tens of TeV up to several PeV reported by the IceCube Collaboration [421–423]. Various possible explanations were proposed including neutrino production through annihilations [424] or decays [425] of the DM particles. However, the observed signal seems to be isotropic and is consistent with the Waxman–Bahcall bound [426], which can be derived from the spectrum of high-energy cosmic rays emitted by astrophysical sources when one takes into account a fraction of energy carried away by neutrinos. This points towards a non-DM origin of the reported anomaly (for recent review see, e.g. [427] and references therein). Future generation of neutrino telescopes should allow to collect more data and therefore clarify this issue.

3.5.3. Limits. As mentioned above, searches for DM-induced neutrinos can provide the strongest up-to-date limits on the spin-dependent cross section \( \sigma_{SD} \) while current limits on the spin-independent component \( \sigma_{SI} \), as well as on the annihilation cross section \( \sigma_{ann} \), remain weaker than the ones derived from DD and ID experiments, respectively.

3.6. X-rays: limits and the 3.5 keV line

In 2014 a possible excess in the x-ray emission near 3.5 keV was reported after analyzing the XMM-Newton data from observations of the Andromeda galaxy and various galaxy clusters with possible connection to decays of sterile neutrino DM [428, 429] (see also e.g. [430, 431]). Subsequently, the signal was confirmed in the data obtained by the Suzaku telescope for core of the Perseus cluster [432], in the XMM-Newton data for the GC [433] and in the deep field observations by NuSTAR [434] and Chandra [435]. Interestingly, such a signal was predicted as a smoking gun for WDM in an early study [436]. In addition to sterile neutrinos, further DM interpretations of the 3.5 keV line were proposed employing, e.g. axion-like particles [437, 438], axinos [439, 440] or gravitinos [441].

The DM interpretation of the line observed in XMM-Newton data was, however, undermined by some of later studies (see, e.g. [442, 443]), as well as by results obtained for several galaxy clusters by the Suzaku telescope [432], XMM-Newton observations of the Draco dwarf galaxy [444] and the HITOMI data for the Perseus cluster [445]. Other explanations were then discussed in the literature including known emission lines from the transitions in potassium and chlorine atoms [442] (see, however, [446]) and charge exchange between bare sulfur ions and neutral hydrogen atoms [447, 448]. In addition, in [442] it was argued that a similar spectral feature is present in the data from the Tycho supernova remnant, where one does not expect to see significant amounts of DM. On the other hand, it was pointed out that the aforementioned null results of experimental searches for the 3.5 keV line are still consistent with the decaying DM interpretation discussed above while other astrophysical explanations might be insufficient to explain the observed excess [56].

At this stage both the DM interpretation, as well as astrophysical explanation of the observed 3.5 keV line cannot be fully excluded.

3.7. LHC mono-X searches

The third classical strategy for WIMP dark matter searches, after direct and indirect detection, is to directly produce a neutral stable particle in high-energy colliders. Since the typical coupling and mass range expected for the WIMP in most scenarios is around or just above EWSB, the LHC can provide in principle an optimal instrument for pursuing this experimental venue.

In fact, the vast majority of the searches for new physics at the LHC are designed to look for events that, besides the rich hadronic/leptonic activity emerging from the decay chain of the produced visible particle, are also characterized by a large amount of missing energy, as this simplifies the task of separating them from the SM backgrounds and optimize the chances for detection. In this sense, then, the discovery of one or more visible particles in a channel characterized by highly energetic jets or leptons, and large missing momentum, would also imply the discovery of a neutral and stable (at least within the detector bounds) particle, which could be part of the dark matter or even all of it.

In many scenarios, however, one contemplates the possibility that the dark matter WIMP is the only new field around the electroweak scale, while additional visible particles, if existing, are sitting beyond the realistic reach of the detector. In this case the detection strategy must involve the identification in the scattering event of one (or a few) isolated, highly energetic, object(s) from initial state radiation (ISR), accompanied by large missing momentum. The object recoiling against the produced invisible particles can be a jet, a gauge boson, or a lepton, so that searches of this typology are commonly referred to in the literature as Mono-X and have generated a great amount of activity and excitement in recent years.

While the LHC mono-X search results have been recast in and applied to numerous models with EW dark matter interactions, and they proved particularly useful in probing compressed spectra in supersymmetry, most official comparisons with the bounds from direct and indirect detection have been presented by ATLAS and CMS in two preferential frameworks: EFT and simplified model spectra (SMS).

In the EFT framework [449–457], which was predominately used by the LHC collaborations for their interpretations in Run 1 [458–463], one derives bounds on the strength of several contact operators, which can be then employed for a
comparison with the limits on $\sigma_p^{\text{SI}}$ and $\sigma_p^{\text{SD}}$ from direct detection searches and neutrino detectors.

The EFT can in principle provide a good approximation as long as the interaction is mediated by particles with mass well above the collision energy. It was however pointed out in several papers [464–469] that one should use special care when comparing the Wilson coefficient bounds arising from mono-X searches with those from underground direct detection searches, as the processes involved happen at widely different scales (the EWSB scale in the former case, and the nuclear scale in the latter). The effects of renormalization group running should be properly taken into account, particularly in cases when operator mixing introduces non-negligible corrections to the expected event rates in underground detectors.

Moreover, at the center-of-mass energies typically probed in a collider environment it is often necessary to consider models defined in terms of renormalizable interactions. By making use of SMS [470–476], one introduces simple renormalizable Lagrangians, characterized by a limited number of free parameters, like the couplings of the dark matter to the visible sector, or the mass of the particles assumed to mediate the interaction between the dark matter and the partons in the nucleons.

In figure 10(a) we show the bounds from the CMS mono-jet search [462] in the $(m_\chi, \sigma_p^{\text{SD}})$ plane at the end of Run 1. Note that the limit is actually placed on the effective coupling, $1/\Lambda^2$, of a dimension-6 axial-vector operator (where running and operator-mixing effects are neglected). The equivalent CMS bound at the end of Run 2 [477] is shown in figure 10(b). It is now expressed in terms of a simplified model with Dirac dark matter, axial-vector mediator, and specific coupling strengths (see [478] for the equivalent ATLAS bound). The typical ‘hook’ shape of the exclusion contour is due to the fact that for any specific dark matter mass the data excludes a range of mediator masses. Additional bounds on the spin-independent cross section, $\sigma_p^{\text{SI}}$, and the annihilation cross section, $\sigma v$, can be found in the experimental papers.

It is worth pointing out that the upper bounds of figure 10 are especially competitive in the low range of the dark matter mass spectrum, as the probability of emission of a high $p_T$ jet drops drastically when $m_\chi$ approaches the $p_T$ cut. Since in the remainder of this review we focus predominantly on WIMPs of mass in the hundreds of GeV to a few TeV range, we will avoid discussing mono-jet bounds in greater detail. Excellent reviews exists in the literature exploring the LHC bounds on a large range of light and not-so-light dark matter scenarios. For a very recent one see, e.g. [9] and references therein.

### 4. The neutralino WIMP as DM

Despite the disappointing failure to discover any superpartners at the LHC (and, in fact, any trace of ‘new physics’), low scale supersymmetry (SUSY) still remains arguably by far the best motivated scenario for ‘new physics’ beyond the standard model. A detailed review of SUSY exceeds the purpose of this work, but numerous extensive reviews exist in the literature (see, e.g. [479–481]). We limit ourselves to recalling a few basic notions that will be relevant for the connection to DM.

#### 4.1. Brief review of supersymmetry and the neutralino as dark matter

SUSY is a space-time symmetry relating each particle of the SM to a partner whose spin differs by 1/2. We only consider here $\tilde{N} = 1$ SUSY, where the space-time algebra is extended by exactly one spinorial SUSY generator, as this is the only case that admits a phenomenology with chiral fermions, and constitutes a straightforward extension of the particle content of the SM.
Initially developed on the basis of aesthetic and ‘proof-of-existence’ considerations, in the eighties it became arguably the most popular solution to the gauge-hierarchy problem. Roughly speaking, if a low-energy effective theory—as the SM is thought to be—includes light fundamental scalar fields, like the Higgs boson, the mass of the scalar particles is subject to strong renormalization by the fields of the UV completion. If the UV completion typical scale is close to the scale of quantum gravity, one needs a fine tuning of approximately 28 orders of magnitude to justify a scalar mass of the order of the EW scale. SUSY provides an attractive solution to this problem thanks to the non-renormalization theorem \[482, 483\] which precludes one-particle irreducible loop corrections to the superpotential so that, as a consequence, mass terms do not get renormalized. In other words, SUSY ‘protects’ the Higgs mass of the SM and makes it technically natural.

Apart from solving the gauge hierarchy problem, SUSY provides a framework that naturally accommodates at the same time several theoretical expectations and a number of experimental data. Low-energy SUSY, in particular, the minimal supersymmetric standard model (MSSM), provides the right particle content for high-scale gauge coupling unification; it furnishes a rationale for the measured values of the mass of the Higgs boson and of the top quark; it provides a natural framework for models of inflation and baryo/leptogenesis; radiative electroweak symmetry breaking (EWSB) can easily be achieved in the MSSM; and, finally, but perhaps most importantly for the scope of this review, some superpartners are weakly interacting and, if stable (or very long lived) are a natural candidate for a WIMP and DM. Among them the most popular one is the lightest neutralino, which we will refer to simply as the neutralino and denote with a symbol \(\chi\) hereafter. Countless studies, starting from \[93, 94\], showed it to be an excellent thermal DM candidate.

We remind the reader that the low-energy Lagrangian of the \(R\) parity-conserving MSSM consists of two parts. One comes from the superpotential, expressed in terms of superfields (marked by carets), which essentially provides a direct supersymmetrization of the Yukawa part of the SM Lagrangian:

\[
W_\text{MSSM} = y_\text{u} \hat{H}_d \hat{Q}_d - y_\text{d} \hat{H}_u \hat{Q}_u - y_\text{e} \hat{H}_d \hat{\nu}_d + \mu \hat{H}_u \hat{H}_d, \tag{4.1}
\]

where the \(y_{\text{u.d.e.}}\) are 3 x 3 Yukawa matrices and \(\mu\) is the Higgs/higgsino mass parameter.

The other part is the so-called ‘soft’ SUSY-breaking Lagrangian, which includes mass terms for the gauginos (Majorana fermion superpartners of the gauge bosons) and for the scalar superpartners of the SM fermions:

\[
\mathcal{L}_\text{soft} = -\frac{1}{2} \left( M_3 \hat{\phi} \hat{\phi} + M_2 \hat{W} \hat{W} + M_1 \hat{B} \hat{B} + \text{c.c.} \right) - \left( a_{\text{u}} \hat{u} \hat{H}_d \hat{Q}_u + a_{\text{d}} \hat{d} \hat{H}_d \hat{Q}_d + a_{\text{e}} \hat{\nu}_d \hat{H}_d \hat{\nu}_d + \text{c.c.} \right) - \frac{g^2}{\sqrt{2}} m_{\tilde{Q}}^2 \tilde{Q} \tilde{Q} - \frac{g^2}{\sqrt{2}} m_{\tilde{L}}^2 \tilde{L} \tilde{L} - \frac{g'}{\sqrt{2}} m_{\tilde{u}}^2 \tilde{u} \tilde{u} - \frac{g'}{\sqrt{2}} m_{\tilde{d}}^2 \tilde{d} \tilde{d} - \frac{g'}{\sqrt{2}} m_{\tilde{\nu}}^2 \tilde{\nu} \tilde{\nu} - G^2 m_{\tilde{\chi}_1}^2 \tilde{\chi}_1 \tilde{\chi}_1 - m_{\tilde{\chi}_1}^2 \tilde{\chi}_1 \tilde{\chi}_1 - m_{\tilde{\chi}_1} \hat{H}_u \hat{H}_d - m_{\tilde{\chi}_1} \hat{H}_d \hat{H}_d - (b \hat{H}_u \hat{H}_d + \text{c.c.}), \tag{4.2}
\]

where \(M_1\) is the mass of the bino, \(M_2\) of the wino, and \(M_3\) of the gluino, which are the fermionic partners of the \(B\), the \(W\) triplet and the gluon octet. The matrices \(m_{\tilde{Q}}^2\), etc., \(a_{\text{u}}\), etc., and \(b\), stand for mass squared, trilinear, and bilinear coefficients for the scalar fields, respectively.

The gauginos transform under the adjoint representation of the respective gauge groups so that, in particular, the bino transforms as a \(U(1)\) phase and three wino states form a triplet of \(SU(2)\). In addition, there exist two more Majorana fermions, the higgsinos of mass \(\mu\), which belong to \(SU(2)\) doublets. The bino and the neutral degrees of freedom of the the winos and the higgsinos have the same quantum numbers and the neutralinos are their mass eigenstates. The masses are obtained by diagonalizing the mass matrix \(M_{\hat{\chi}}\) given by

\[
M_{\hat{\chi}} = \begin{bmatrix}
M_1 & 0 & -\frac{g}{\sqrt{2}} v_d & \frac{g'}{\sqrt{2}} v_a \\
0 & M_2 & \frac{g}{\sqrt{2}} v_d & -\frac{g'}{\sqrt{2}} v_a \\
-\frac{g}{\sqrt{2}} v_d & \frac{g}{\sqrt{2}} v_d & 0 & -\mu \\
\frac{g'}{\sqrt{2}} v_a & -\frac{g'}{\sqrt{2}} v_a & -\mu & 0
\end{bmatrix}, \tag{4.3}
\]

where \(g\) and \(g'\) are \(SU(2)\) and \(U(1)\) gauge couplings, respectively, and \(v_d\) and \(v_a\) are the vevs of the neutral components of the Higgs doublets \(H_u\) and \(H_d\).

While it is the mass eigenstates that are the physical states, they can be dominated by some gauge eigenstates which allows one to make convenient approximations. In the limit where one among \(M_1, M_2\), and \(\mu\) is much smaller than the other parameters, the lowest eigenvalue approximately coincides with the lightest of these masses. In other words, \(m_{\tilde{\chi}} \approx M_1\) when \(M_1 \ll M_2, \mu\), and so on for interchanging orders. When two or more masses are instead comparable, mixing effects come into play and can change the phenomenology. In this context, it became clear after the LHC Run 1 and beginning of Run 2 that gaugino and higgsino masses are likely to be well above the Higgs vevs, i.e. \(M_1, M_2, \mu \gg v_u, v_d\).

The most popular extension of the MSSM is arguably the next-to-minimal supersymmetric standard model (NMSSM), which can provide an elegant solution to the \(\mu\) problem (see, e.g. \[484\] for a comprehensive review). In the NMSSM there is one additional kind of neutralino, the singlino, which is the fermionic partner of the gauge singlet Higgs field\[19\]. Because of the presence of the singlino, the NMSSM can sometimes present complementary DM signatures with respect to the MSSM.

The neutralinos, being electric and color charge-neutral, interact with the SM with the strength of the weak interaction. The lightest among them, if it is the lightest supersymmetric particle (LSP), is stable provided an additional discrete symmetry (\(R\)-parity) is assumed. Note, incidentally, that \(R\)-parity violation is in general strongly constrained by bounds on proton decay and precision tests of the SM \[70\]. Below we will review the properties of the neutralino and the present status of this important candidate that has become over time the paradigm of WIMP DM.

4.2. Neutralino relic abundance

We will now discuss in more detail the mechanisms that can lead to the correct value of the neutralino DM relic density.

\[19\] In the NMSSM the superpotential includes additional terms involving a gauge singlet chiral superfield \(S\), i.e. \(W \supset \lambda S H_u H_d + \kappa/3 S^3\).
As we will see, this often requires going beyond the simplest WIMP picture that we discussed in section 2.2.1. In particular, for the bino-like neutralino (i.e. for \( m_\chi \approx M_1 \)), which early on [485] was the most favored scenario in SUSY models with gaugino mass unification at the GUT scale, one typically obtains too small an annihilation cross section and, therefore, exceedingly large values of the DM relic density. However, this can be improved by assuming specific mass patterns for the neutralinos and some other SUSY particles.

4.2.1. Coannihilations. One of the most important mechanisms where specific mass relations between the LSP and some other states determine the relic abundance is coannihilations (see section 2.2). In phenomenologically interesting scenarios the lightest neutralino can be mass degenerate with some heavier supersymmetric species (which usually is the next-to-lightest supersymmetric particle, or NLSP) thus fulfilling some of the conditions where coannihilations can play a major role in determining the DM relic density. The mass degeneracy can lead to either a decrease or an increase of the final relic abundance, depending on whether the NLSP freeze-out occurs later or earlier than for the LSP.

The neutralino-chargino mass degeneracy plays a major role in determining \( \Omega_\chi h^2 \) for a wino- or higgsino-like neutralino. This is due to characteristic mass degeneracies between the higgsino-like (in which case \( m_\chi \approx \mu \)) or the wino-like (with \( m_\chi \approx M_2 \)) neutralino and the lightest chargino or the second lightest neutralino that appear naturally in the MSSM—recall that higgsinos are \( SU(2) \) doublets and winos are \( SU(2) \) triplets.

The correct value of \( \Omega_\chi h^2 \) can be obtained without assuming any special mass relations. This is mainly due to the fact that the most efficient annihilation and coannihilation channels are in this case determined by the processes whose strength is set by the respective gauge couplings. As a result, the relic abundance \( \Omega_\chi h^2 \sim 1/\sigma_{\text{ann}} \sim m_\chi^2/g^4 \) shows a simple parabolic dependence on the neutralino mass.

The wino and, to a much lesser extent, higgsino relic density are also influenced by the Sommerfeld enhancement which is the enhancement of the annihilation cross section due to a modification of the Yukawa potential induced by the electroweak gauge bosons [486] (see also [487, 488] for a recent discussion). This effect is particularly important in the wino mass range for which one obtains \( \Omega_\chi h^2 \approx 0.12 \), which is then broadened to \( M_2 \approx 2–3 \) TeV. Although the Sommerfeld enhancement is most important for a nearly pure wino, it can also play a role for a mixed wino/higgsino state, thus modifying the relevant area of the so-called relic neutralino surface in the parameter space at which the correct value of the relic density is achieved [489]. In the case of the higgsino-like neutralino the relic density is reduced mainly thanks to a triple mass degeneracy between the two lightest neutralinos and the lightest chargino [490]. As a result, the correct \( \Omega_\chi h^2 \) is obtained for \( m_\chi \approx 1 \) TeV—we will refer to it as the \( \sim 1 \) TeV higgsino region.

In the case of bino-like lightest neutralino an important role in determining the relic density is played by stau coannihilation [491–493] when the LSP is mass-degenerate with the lightest stau, \( m_\chi \approx m_\tilde{\tau}_1 \lesssim 400–500 \) GeV for \( \Omega_\chi h^2 \approx 0.12 \). The same effect can be obtained for other sleptons. On the other hand, coannihilations of higgsino-like or wino-like DM with sleptons lead to an increase of the relic density [494]. Interestingly, thanks to this effect one can obtain \( \Omega_\chi h^2 \approx 0.12 \) for higgsino mass as small as \( m_\chi \approx 600 \) GeV [208].

Coannihilations with squarks can lead to the correct value of the lightest neutralino relic density for a significantly heavier neutralino. In particular, such coannihilations can occur with the lightest stop [495], \( \tilde{t}_1 \), or with the lightest sbottom, \( \tilde{b}_1 \), which are often the lightest squark states [496]. A similar mechanism leads to a reduction of \( \Omega_\chi h^2 \) for a heavy neutralino mass-degenerate with the gluino, i.e. when \( m_\chi \approx m_\tilde{g} \) [497]. For both the stop and gluino coannihilation it is possible to obtain \( \Omega_\chi h^2 \approx 0.12 \) for \( m_\chi \) as large as 6–9 TeV when the Sommerfeld enhancement and gluino-gluino bound-state effects are incorporated [498, 499], although this should not be treated as a strict upper limit on phenomenologically acceptable values of \( m_\chi \).

In the framework of the NMSSM a nearly pure singlino, which can be the lightest neutralino, typically interacts very weakly. It annihilates mainly into scalar-pseudoscalar pairs, with the associated couplings proportional to \( \kappa \) or \( \lambda \) (see footnote 19), which are typically small. As a result, the singlino relic density is often too large. However, this can be improved thanks to coannihilations with an higgsino, a wino, a stau/neutrino, a stop, or a gluino (for a detailed discussion see [500]).

4.2.2. Funnels. Another important mechanism that can enhance neutralino pair annihilation and lead to the correct value of the relic density of neutralino DM in the MSSM is due to annihilations via the resonant \( s \)-channel exchange of the Z-boson, the light Higgs \( h \) [501], and/or heavy (pseudo) scalar Higgs bosons \( H \) and \( A \), in the respective resonance (or funnel) regions of the parameter space [502] if the exchanged particle mass \( m \) is roughly twice \( m_\chi \). In a more precise treatment this condition is slightly modified by taking into account the thermal average of the relative velocity of annihilating neutralinos in the early Universe. Hence both the \( Z \)-resonance and the \( h \)-resonance regions require a light neutralino \( (m_\chi < 100 \) GeV), as \( m_H = 91 \) GeV and \( m_A = 125 \) GeV. On the other hand, in the \( A \)-funnel region the lightest neutralino can be much heavier. In the NMSSM, where the Higgs spectrum is richer, accordingly more resonance channels are in principle possible.

4.2.3. Other mass patterns. In the absence of any accidental mass patterns, the bino annihilation rate is typically dominated by a \( t \)-channel slepton exchange, \( \chi \chi \rightarrow \tilde{t} \tilde{t} \), and consequently \( \Omega_\chi h^2 \sim m_t^4/m_\chi^2 \) is also sensitive to the mass of the lightest slepton, \( m_\tilde{t} \) [485, 502]. This can lead to the bino relic density spanning a few orders of magnitude depending on both relevant masses. In particular, one can obtain \( \Omega_\chi h^2 \approx 0.12 \) if \( m_\tilde{t} \ll m_\chi \lesssim 150 \) GeV, in the so-called bulk region [75, 485, 502].

Another important option is associated with a general mixed bino-higgsino LSP. In the mass range \( 100 \) GeV \( \lesssim m_\chi \lesssim 1 \) TeV...
a nearly pure higgsino $\chi$ typically yields too small a value of the relic density (while for a pure bino it is typically too large). This can be circumvented for choosing an appropriate (‘well-tempered’) admixture of $\tilde{B}$ and $\tilde{H}_{u,d}$. In the context of GUT-constrained SUSY models such a scenario can be realized in the so-called hyperbolic branch/focus point region [503, 504]. The annihilation rate in this case is dominated by neutralino annihilations into gauge bosons, as well as through a $t$-channel exchange of a higgsino-like chargino and/or the second lightest neutralino.

Among other scenarios with mixed neutralino LSP that have been discussed in the literature one can distinguish the mixed bino-wino (see, e.g. [505–507], singlino-higgsino (in the context of the NMSSM) [500] or even bino-higgsino-wino (see, e.g. [508, 509]) states.

One loop corrections to annihilation cross sections can provide some improvement in the computation of the neutralino relic density that can introduce corrections of the order of the observational error and therefore should be taken into account when estimating the uncertainty of the determination of $\Omega_\chi h^2$ (see, e.g. [510, 511] or recent [512, 513] and references therein).

4.3. Simplest models defined at the GUT scale: the CMSSM and the NUHM

As was mentioned above, the MSSM can feature many non-trivial phenomenological signatures and it is important to understand that predictions in different sectors of the theory can be intertwined.

In this subsection, we show how these relations affect the DM predictions in two popular SUSY models with simple unified, or constrained, boundary conditions set at the GUT scale, the constrained MSSM (CMSSM) [514] and the non-universal Higgs model (NUHM) [515]. The CMSSM, inspired by supergravity constructions, is characterized by a set of four parameters defined at the GUT scale: the unified scalar and gaugino masses, $m_0$ and $m_{1/2}$, respectively; the unified trilinear coupling $A_0$; ratio of the Higgs vevs $\tan \beta$, and the sign of the $\mu$ parameter. In the NUHM, one instead does not assume the soft Higgs masses $m_{\tilde{H}_u}$ and $m_{\tilde{H}_d}$ to be unified with the other scalar masses at the GUT scale, thus introducing two additional free parameters. For many years these models remained an important playground for SUSY phenomenology in the context of unification. In particular, we focus on the implications of the recently discovered the Higgs boson with mass close to 125 GeV and the nature and associated discovery prospects of the DM.

In section 4.4, we extend the analysis to a more general case of the phenomenological MSSM (pMSSM), which roughly encompasses the remainder of signatures and possibilities for the discovery of neutralino DM in the general MSSM.

First, however, we discuss important implications of the properties of the Higgs boson discovered at the LHC on the expected mass range of superpartners. As we will see, in the framework of unified SUSY models this will have important ensuing implications for the nature and discovery prospects of WIMP DM in this class of models.

4.3.1. Implications of the Higgs boson for SUSY breaking scale

In the MSSM the mass of the Higgs boson is not a free parameter of the theory, in contrast to the SM. Its value is calculated in terms of the parameters of the model. Since the quartic couplings of the Higgs fields are roughly given by the EW gauge couplings, the tree-level value of the Higgs mass presents an upper bound determined by the mass of the $Z$ boson, $M_Z$. As a consequence, the observed value of the Higgs mass, $m_h = 125$ GeV, implies the presence of significant radiative corrections, which increase logarithmically as the SUSY scale increases.

It is convenient to express the dominant 1-loop contribution to the radiative corrections of the Higgs mass in terms of the stop mass and stop mixing (see, e.g. [516]),

$$\delta m_h^2 \sim \frac{3y_t^4}{16\pi^2} \sigma^2 \left[ \ln \left( \frac{M_{\text{SUSY}}^2}{m_t^2} \right) + \frac{X_t^2}{M_{\text{SUSY}}^2} \left( 1 - \frac{X_t^2}{12M_{\text{SUSY}}^2} \right) \right].$$

(4.4)
where $y_t$ and $m_t$ are the top Yukawa coupling and the top quark mass computed in the $\overline{MS}$ scheme, respectively, $v = \sqrt{v_u^2 + v_d^2} \approx 246$ GeV is the EW vev, the SUSY scale is set at the geometrical average of the stop masses, $M_{\text{SUSY}} = \sqrt{m_{\tilde{t}_1}m_{\tilde{t}_2}}$, and $X_t = A_t - \mu \cot \beta$ gives the main stop mass matrix off-diagonal term.

Equation (4.4) is sufficient to describe the qualitative behavior of the Higgs boson mass but higher-order corrections are necessary to obtain a more precise quantitative estimate of the favored value of $M_{\text{SUSY}}$ after the Higgs discovery.

Several numerical codes are available to calculate the Higgs mass in terms of the MSSM parameters. The results are subject to significant uncertainty, which is due to missing higher-order loop corrections, the choice of renormalization scheme, etc. Figure 11(a), taken from [517], presents a comparison of the Higgs mass obtained by different codes. The dependence on the geometrical average of the stop masses, $M_{\text{SUSY}}$, is presented in the MSSM. Figure 11(b), taken from [518], shows in the plane $(m_0, m_{1/2})$ of the CMSSM the 1σ and 2σ regions of marginalized 2-dimensional posterior probability density function (pdf) consistent with the Higgs mass, taking into account errors, both experimental (which have since decreased considerably) and theoretical (which are estimated at the level of 2–3 GeV). One can see that the measured Higgs mass value alone suggests typical superpartner masses to be in the multi-TeV range. Strictly speaking, in phenomenological models like the phenomenological MSSM (pMSSM) this conclusion applies to the masses of the stops, but in unified models this sets the overall scale of SUSY breaking, since in those models superpartner masses are related by boundary conditions in the UV. Note, that no additional conditions, in particular of satisfying the relic density constraint, have been imposed here.

We stress that the above conclusion applies not only to the CMSSM, but to a much wider class of models, some equally well inspired by supergravity, like the NUHM and non-universal gaugino mass models, and other ones for which SUSY breaking is transmitted to the visible sector via other high-scale messengers, like in the case of gauge mediation. On the other hand, multi-TeV expectations for the scale of superpartner masses are independently supported by increasingly stringent lower limits from the LHC and by the lack of any convincing departure from standard model values of rare processes involving flavor, e.g. $b \to s\gamma$, $B_s \to \mu^+\mu^-$, etc.

### 4.3.2. Neutralino DM in unified models in light of LHC and other recent data.

The requirement that the neutralino relic density is close to the observed value places an additional strong constraint on unified SUSY models. (In contrast, the impact of limits from direct searches for DM has not been as strong as that from collider searches [519].) In these models this additionally implies specific properties for the neutralino LSP and, therefore, for DM searches.

A large number of global studies (see, e.g. [209, 518, 520–536]) has been performed over the recent years in which the parameter space of the CMSSM was confronted with a broad set of experimental constraints on several observables: the Higgs mass and the Higgs decay rates in different channels at the LHC; the value of the relic density as measured by PLANCK (and previously WMAP); the lower bounds on SUSY masses as directly measured by CMS and ATLAS;...
the measured values of several $B$-physics rare decays like, e.g. $\text{BR}(B \rightarrow X\gamma)$, $\text{BR}(B_s \rightarrow \mu^+\mu^-)$, or $\text{BR}(B_d \rightarrow \tau\nu)$; the measurement of the anomalous magnetic moment of the muon, $\delta(g - 2)_\mu$, which shows a $\sim 3\sigma$ discrepancy with the SM value. In the modern, state-of-the-art approach, these constraints are generally implemented via a global likelihood function, constructed to compare the measured value of the observables with their calculated values in the SUSY parameter space. Observables are usually calculated with sophisticated numerical codes, and the likelihood function is used to determine statistically preferred likelihood (if one performs a frequentist analysis based on the profile likelihood) or, alternatively, credibility (if one performs instead a Bayesian analysis based on the posterior probability) regions of the parameter space.

In figure 12(a) we present the $1\sigma$ and $2\sigma$ Bayesian credibility regions of the marginalized posterior probability in the $(m_0, m_{1/2})$ plane of the CMSSM. The figure presents an updated version of plots previously shown in [518] and [209], obtained now by incorporating in the likelihood function the most recent constraints from direct squark and gluino searches at the LHC [537] (we use the code of [538] to recast the experimental data) and the recent constraints from direct searches of DM in LUX [170]. In figure 12(b) we show the $1\sigma$ and $2\sigma$ likelihood regions in the $(m_0, m_{1/2})$ plane of the CMSSM, following from a frequentist analysis of [539]. The color code is used to indicate the different mechanisms by which the correct relic density of the neutralino is obtained in the early Universe, see section 4.2.

Note that credibility and likelihood regions are not extremely dissimilar from one another (within the overlapping ranges of $m_0$ and $m_{1/2}$) despite the very different concepts of statistics applied in both panels. In the bottom left corner of figure 12(a) one can see a Bayesian credibility ‘island’, representing the bulk of the $A$-funnel region and a faint appearance of the stau-coannihilation region surviving the most recent LHC bound, in agreement with figure 12(b). This is the region of the parameter space where the neutralino is predominantly bino-like.

In figure 12(a) the parameter space is scanned to larger values of $m_0$ and $m_{1/2}$, well into the TeV-scale region that most easily allows one to accommodate the correct value of the Higgs mass. This region features the existence of a second, and actually larger, ‘island’ in the parameter space, characterized by an almost pure higgsino-like neutralino that, as was explained in section 4.2, is characterized by the LSP higgsino-like mass around 1 TeV in order to give the correct relic density. Frequentist analysis also shows the emergence of this region, despite the smaller region of $m_0$ and $m_{1/2}$ covered in figure 12(b).

Taking the view that the Higgs mass implies a multi-TeV scale of superpartners, having the LSP at 1 TeV without having to adhere to any special mechanism for obtaining the right $\Omega_\chi h^2$ appears to be a rather intriguing and well motivated solution [519], with promising prospects for DM searches, as discussed below.

4.3.3. Prospects for WIMP searches in GUT-constrained models. Contours of the 68% and 95% Bayesian credible region of the CMSSM in the $(m_0, \sigma_p^{SI})$ plane are shown in figure 13(a), which updates the equivalent plots presented in [518] and [209]. As stated above, the likelihood function includes the recently published LUX data [170], which we have
incorporated here following a procedure similar to [360]. Note that in recent years several numerical codes have been devised to appropriately account for DD data in the form of a likelihood function, see [541–544]. To facilitate comparison, we mark as a solid gray line in figure 13(a) the 90% C.L. upper bound as given by the LUX collaboration. The newest results from XENON1T [169] are shown instead as a solid red line.

Note how parts of the 95% credible posterior regions extend somewhat above the 90% C.L. limit given by the experimental collaboration. This is due, on the one hand, to the non-negligible difference that exists between the 90% and 95% confidence bound (which [545] did not take into account) when the likelihood function is not very steep over the parameter space. On the other hand, as the likelihood function’s slope is quite gentle, the probability density shows some sensitivity to the choice of Bayesian priors, which in this case pull towards larger values of \( \sigma_p^{SI} \) by favoring lighter gauginos. If, for instance, a linear (flat) prior was chosen instead, then the \(~1\) TeV higgsino would become even more pronounced. However, the corresponding ranges of \( \sigma_p^{SI} \) are not as much prior-dependent. For completeness, we superimpose to the plot a set of viable scan points in (blue) that, while drawn from the posterior probability density, delimit the extension of the 95% C.L. profile-likelihood region. It is important to note that in the models with unified gaugino masses at the GUT scale, e.g. the CMSSM, one typically does not obtain nearly pure higgsino DM, for which \( \sigma_p^{SI} \) could be arbitrarily low, as it is seen in the low-energy MSSM. Once gaugino masses are allowed to grow large to minimize their mixing with the higgsino component, also the SM-like Higgs boson mass increases due to the impact of gaugino mass parameters on the RGE running of the stop and soft Higgs masses. Precise determination of the lower limit on \( \sigma_p^{SI} \) is sensitive to the accuracy of the calculation of \( m_h \). The results presented in figure 13(a) correspond to \( m_h \) obtained with FeynHiggs 2.10.0 [546, 547].

Figure 13(a) shows the same two regions featured in figure 12(a): the A-funnel on the left, and the \(~1\) TeV higgsino on the right. The latter clearly presents the better prospects for the reach of tonne-scale underground detectors, which we can feature slightly different choices for the set of constraints or in the number of input parameters (see, e.g. [539, 551, 552]). Note that the constraints from the 2016 LUX results [170] are implemented in the likelihood function, so that the region marked by gray points, which was belonging to the \( 2\sigma \) region in [208], is now shown as excluded at the 95% C.L. bound from XENON1T [169], not included in the likelihood function. One can see that there are countless possibilities for a neutralino DM in agreement with all the relevant constraints.

In addition, it is possible to have accidental cancellations in the neutralino couplings to the \( Z \) and \( h \) bosons, as well as cancellations between the heavy and light Higgs diagrams, which

4.4. The pMSSM

As we have seen in section 4.3, the \(~1\) TeV higgsino seems to be an attractive candidate for WIMP DM in SUSY models with boundary conditions defined at the GUT scale, and it features very good potential for a timely detection in one-tonne detectors.

Low energy SUSY is a very broad framework, able to accommodate several possibilities for the spectrum of superpartners. As SUSY must be broken in a hidden sector, little is known about the most likely mass pattern for the supersymmetric particles, and one must rely on reasonable assumptions driven by theory considerations. Thus, in order to analyze DM signatures in a general and model-independent SUSY scenario we analyze here the DM issue in the phenomenological MSSM (pMSSM).

The pMSSM [548] is the most general parametrization of the MSSM, based only on assumptions of minimal flavor violation, \( R \)-parity conservation, and a level of CP violation not exceeding that of the SM. These assumptions reduce the over hundred free parameters potentially present in equation (4.2) of the MSSM down to 19, all defined at the SUSY scale. It is easy to see that all the scenarios discussed in section 4.3 can be described in this framework by choosing appropriate boundary conditions. The same is true for other popular scenarios for SUSY breaking like, e.g. anomaly mediation [549, 550].

Since the number of free parameters in the pMSSM remains quite large, there is no real issue in fitting all the constraints belonging to the standard set described above. In particular, \( \Omega_\chi h^2 \approx 0.12 \)—in addition to all relevant collider constraints—can be fairly easily satisfied in different parts of the parameter space for different neutralino WIMP compositions.

We show in figure 14(a) the \( 2\sigma \) region in the \((m_\chi, \sigma_p^{SI})\) plane of the pMSSM, emerging from the profile likelihood of the global constraints. The neutralino composition of the points in green is 90% or more bino-like; points in red are for more than 90% higgsino-like; and points in blue are at least 90% wino-like. Bino/higgsino admixtures are shown in gold, wino/higgsino in magenta, and wino/bino in cyan. Figure 14(a) updates the equivalent plot of [208], but a similar picture emerges in pMSSM global analyses by other groups, which can feature slightly different choices for the set of constraints or in the number of input parameters (see, e.g. [539, 551, 552]). Note that the constraints from the 2016 LUX results [170] are implemented in the likelihood function, so that the region marked by gray points, which was belonging to the \( 2\sigma \) region in [208], is now shown as excluded at the 95% C.L. We also show with a solid red line the recent 90% C.L. bound from XENON1T [169], not included in the likelihood function. One can see that there are countless possibilities for a neutralino DM in agreement with all the relevant constraints.

As SUSY must be broken in a hidden sector, little is known about the most likely mass pattern for the supersymmetric particles, and one must rely on reasonable assumptions driven by theory considerations. Thus, in order to analyze DM signatures in a general and model-independent SUSY scenario we analyze here the DM issue in the phenomenological MSSM (pMSSM). The pMSSM [548] is the most general parametrization of the MSSM, based only on assumptions of minimal flavor violation, \( R \)-parity conservation, and a level of CP violation not exceeding that of the SM. These assumptions reduce the over hundred free parameters potentially present in equation (4.2) of the MSSM down to 19, all defined at the SUSY scale. It is easy to see that all the scenarios discussed in section 4.3 can be described in this framework by choosing appropriate boundary conditions. The same is true for other popular scenarios for SUSY breaking like, e.g. anomaly mediation [549, 550]. Since the number of free parameters in the pMSSM remains quite large, there is no real issue in fitting all the constraints belonging to the standard set described above. In particular, \( \Omega_\chi h^2 \approx 0.12 \)—in addition to all relevant collider constraints—can be fairly easily satisfied in different parts of the parameter space for different neutralino WIMP compositions.

We show in figure 14(a) the \( 2\sigma \) region in the \((m_\chi, \sigma_p^{SI})\) plane of the pMSSM, emerging from the profile likelihood of the global constraints. The neutralino composition of the points in green is 90% or more bino-like; points in red are for more than 90% higgsino-like; and points in blue are at least 90% wino-like. Bino/higgsino admixtures are shown in gold, wino/higgsino in magenta, and wino/bino in cyan. Figure 14(a) updates the equivalent plot of [208], but a similar picture emerges in pMSSM global analyses by other groups, which can feature slightly different choices for the set of constraints or in the number of input parameters (see, e.g. [539, 551, 552]). Note that the constraints from the 2016 LUX results [170] are implemented in the likelihood function, so that the region marked by gray points, which was belonging to the \( 2\sigma \) region in [208], is now shown as excluded at the 95% C.L. We also show with a solid red line the recent 90% C.L. bound from XENON1T [169], not included in the likelihood function. One can see that there are countless possibilities for a neutralino DM in agreement with all the relevant constraints.
result in the suppression of direct detection cross section in so-called blind spot regions of the parameter space [553–556] (see [557] for a recent study). Several points characterized by bino/higgsino admixtures, shown in gold color in figure 14(a), must belong to blind spots to evade the most recent DD bounds. It has been shown, e.g. in [558], that LHC searches for heavy Higgs bosons in the $\tau^+\tau^-$ channel are currently extensively probing much of the parameter space giving rise to these special regions.

The strongest indirect limits on the spin-dependent scattering cross section for neutralino DM with mass exceeding the $\sim 100$ GeV range are given by IceCube/DeepCore [559–561] and ANTARES [403, 562], from observation of neutrinos from the Sun.

In figure 14(c) we show the reach of several $\gamma$-ray indirect detection searches in the $(m_\chi, \sigma_p)$ plane of the pMSSM.
with $\Omega h^2 \approx 0.12$, as a function of the branching fraction $\text{BR}(\chi\chi \rightarrow W^+ W^-)$. The figure is taken from [563]. The points with $m_\chi \approx 2$–3 TeV and large branching ratio to $W^+ W^-$ are those characterized by a large wino composition (see figure 14(a)). As these points are subject to the Sommerfeld enhancement [564, 565], a non-perturbative effect that can give a significant boost to the annihilation cross section, they appear to be in tension with observations from the Galactic Center at the Cherenkov telescope H.E.S.S. [566]. The extent of the tension depends of course on the choice of halo profile. This was observed first in [567–569]. The $\sim 1$ TeV higgsino region can also be seen in figure 14(c), for slightly lower $\sigma v$, and characterized by $\text{BR}(\chi\chi \rightarrow W^+ W^-) \approx 0.5$, as the remaining 50% is dominated by the $Zh$ final state.

One can see in figure 14(c) that the Cherenkov telescope array (CTA), with $\sim 500$ h of observation of the Galactic Center, will probe most of the pMSSM parameter space with DM mass in the TeV range. We make the point again that in the majority of SUSY models with parameters defined at some high scale this is the region emerging as favored after the discovery of the Higgs boson at 125 GeV. Thus, CTA will prove to be an indispensable instrument to probe ranges of SUSY-model parameters that would otherwise be entirely out of reach by other direct means.

To highlight the idea of complementarity, we show in figure 15(a) the reach of CTA with 500 h of observation of the Galactic Center, compared to the reach of 1-tonne detectors in the $(m_\chi, \sigma_p^{SI})$ plane. The color code is explained in the caption. In figure 15(b) we present the equivalent picture in the $(m_\chi, \sigma_p^{SD})$ plane, compared to the estimated IceCube reach. And finally, we show in figure 15(c) the reach of CTA compared to the present limits on stop mass obtained in simplified models at the LHC. Figure 15 is taken from [208]. Improvements in the LHC limits are not expected to have any effect on the sensitivity of CTA. Indeed, CTA remains sensitive to spectra where the gluinos and squarks lie well beyond the reach of present and future colliders.

4.5. Going beyond standard assumptions

In this topical review we have focused on reasonable but simplest underlying assumptions about DM that are usually made in phenomenological studies of the subject. One is that the DM in the Universe comprises (or is dominated by) just one species. This translates into insisting that its relic density saturates the measured value of about 0.12. However, as we already mentioned in section 2.2.2, the correct WIMP DM relic density can be obtained even if the relevant annihilation rate varies from the canonical thermal value. Another usually made assumption, or actually set of assumptions, is that, in the early Universe DM particles were generated only (or mostly) through their freeze-out out of thermal equilibrium. Although these assumptions are certainly sensible, neither of them is necessarily correct. It is therefore interesting to see how various results and conclusions derived in the literature can be affected by going beyond the standard freeze-out paradigm. In this section we will briefly illustrate
this with a few examples in the context of neutralino DM. For a more comprehensive review see, e.g. [10].

4.5.1. Multi-component DM. There is really no reason, other than simplicity, to insist that the whole of DM is made up of just one species of particles. There exist several scenarios, in SUSY or not, where this is not necessarily the case. In fact, the idea that, for instance, the neutralino and the axion—arguably the two DM candidates most strongly motivated by particle physics—could easily co-exist in the Universe in basically any proportion has been around for decades. As was mentioned in section 4.2, this can be motivated by insisting on keeping the scale of SUSY breaking as low as possible, in order to reduce the level of fine tuning among SUSY parameters. In such regions of the parameter space where the neutralino is close to a pure higgsino (or a pure wino), the relic density of DM is too low as DM mass is not large enough. This can also be consistently realized in specific, well motivated models [570–572]. Other possibilities include employing an additional, non-thermal component [573].

We illustrate this in figure 16. We can see that prospects for WIMP detection remain good, despite lower number density. For earlier works reaching similar conclusions, see, e.g. [575].

4.5.2. Low reheating temperature. It is usually assumed that, when WIMPs freeze out the thermal plasma, the Universe has already reached radiation dominated (RD) thermal equilibrium. In other words, the value of the reheating temperature $T_R$, which marks the onset of the RD epoch, is assumed to be much larger than the freeze-out temperature. This does not have to be the case and can strongly alter our conclusions about WIMP DM properties.

Low $T_R$ can result from an extended reheating period in the evolution of the Universe after an inflationary epoch. In addition to modifying the DM population from freeze-out, it can also be changed by an additional entropy production from decays of some heavy species that took place after the DM freeze-out. As a result one can either reduce or increase the DM relic density depending on whether the additional entropy production is accompanied by efficient direct and/or cascade decays of the heavy field to the DM particles.

From the phenomenological point of view, this mechanism allows one to fit the relic density constraint for almost any scenario with neutralino DM [576, 577] (for a recent discussion, see [77]). We illustrate this in figure 17(a) where the lines of constant $\Omega_{\chi}h^2 = 0.12$ are shown for several values of the reheating temperatures, $T_R = 1,10,50,100,200$ GeV as a function of the neutralino DM mass and $\Omega_{\chi}h^2$ (high$T_R$), i.e. the value of the DM relic density corresponding to the standard cosmological scenario with high $T_R$. In particular one can see that for $T_R \approx 100$ GeV the correct value of $\Omega_{\chi}h^2$ for higgsino DM can be obtained for masses significantly larger than 1 TeV. Such a heavy higgsino can still be within the reach of one-tonne detectors, as can be seen in figure 17(b), where we show the direct detection spin-independent cross section, $\sigma_p$, as a function of $m_{\chi}$, for phenomenologically favored points in the p10MSSM obtained assuming $T_R = 100$ GeV [77].

5. Summary and conclusions

It is not easy to look for the invisible but, in the case of DM, it is certainly worth the effort. A detection of a DM signal is likely not only to confirm the common belief that most of the

Figure 17. (a) Contours (black dotted) of constant $\Omega_{DM}h^2 = 0.12$ for different values of the reheating temperature, $T_R$, in the MSSM, in the $(m_{DM},\Omega_{DM}h^2(\text{high}T_R))$ plane, where $\Omega_{DM}h^2(\text{high}T_R)$ corresponds to the standard cosmological scenario for which the correct value of the neutralino relic density is obtained along the the solid black horizontal line. Green squares correspond to bino DM, red triangles to higgsino DM and blue diamonds to the wino DM case. Negligible direct and/or cascade decays of the inflaton field are assumed. (b) Direct detection cross section, $\sigma_p^{SI}$, as a function of $m_{\chi}$ in the ten-parameter subset of the MSSM (p10MSSM) for which 95% C.L. region (including the relic density constraint) for $T_R = 100$ GeV is shown. The solid (dashed) black lines correspond to LUX (projected XENON1T) limit on $\sigma_p^{SI}$. Color coding as in the left panel. Reproduced from [77]. CC BY 4.0.
dark mass in the Universe is made up of WIMPs but to hope-
fully shed some light on the particle physics framework that it
is part of. In this topical review we have provided an overview
of the current experimental situation, paying particular atten-
tion to current bounds and recent claims and hints of a possible
signal in a wide range of experiments. On the particle physi-
cics side, we reviewed several candidates for explaining the
DM, concentrating mostly on the class of WIMPs that could
be produced mostly through the freeze-out mechanism. We
have paid attention to the neutralino of SUSY since it remains
the most strongly motivated candidate that additionally shows
excellent detection prospects. We have emphasized that
the currently most interesting—in our opinion—case of ~1 TeV
higgsino-like neutralino in unified SUSY models will nearly
fully be tested in the new tonne-scale underground detectors
which are coming online. However, one should remember
that, even if eventually a genuine DM signal is detected, then
it is likely that several measurements will have to be made in
both direct and indirect detection experiments—and this will
likely be possible only under rather favorable conditions—in
order to shed some light on the actual nature of the WIMP.

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