Identification of Dark Matter Particles

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Abstract. A reliable identification of Dark Matter particles can probably be achieved only through a combined analysis of accelerators, direct and indirect searches. I review here the status of these detection strategies, and discuss how to combine them in a self-consistent way, keeping into account all astrophysical uncertainties.

1. Introduction

Dark Matter (DM) is a fundamental ingredient of the Standard Cosmological model, which provides a satisfactory (albeit not perfect) explanation of a wide range of observations in Astrophysics and Cosmology [1, 2, 3, 4, 5, 6]. In the framework of this model, we can determine the abundance of DM in the Universe with good accuracy [7]; we have an increasingly accurate understanding of how DM is distributed in astrophysical structures, from Dwarf Galaxies up to to Clusters of galaxies, based on high-resolution numerical simulations [8], and to gravitational lensing observations [9]; we even have a rather precise idea of how the Milky Way has formed, and of what the local abundance of DM is [10, 11, 12, 13]. Furthermore, we know today that DM cannot be made of ordinary matter, so new particles must exist [14], unless we are completely misled by astrophysical and cosmological observations at all scales.

The need for new particles has prompted particle physicists to propose literally tens of possible DM candidates. Axions [15, 16], for instance, are hypothetical particles whose existence was postulated to solve the so called strong CP problem in Quantum Chromo Dynamics, and they are known to be very well motivated DM candidates. Other well-known candidates are Sterile Neutrinos [17, 18], which interact only gravitationally with ordinary matter, apart from a small mixing with the familiar neutrinos of the Standard Model. A wide array of other possibilities have been discussed in the literature, and they are currently being searched for with a variety of experimental strategies [3, 4].

The most studied class of candidates is that of WIMPs (for weakly interacting massive particles), which have the virtue of naturally achieving the correct relic abundance in the early Universe. The reason why they became so popular is that WIMP candidates arise naturally from theories that seek to extend the Standard Model of particle physics, and to embed it in a more fundamental theory. In particular, it was noticed back in 1983 that one of the most promising extensions of the Standard Model, Supersymmetry (SUSY), provides an excellent Dark Matter candidate: the neutralino [19, 20, 21, 22]. This particle fulfills all the properties of the good Dark Matter candidate, and it has become over the years a prototypical example of WIMPs. Its mass can range from about 50 GeV to a few TeV, and its interaction cross section with ordinary
matter and with itself are such that it can account for all the Dark Matter in the Universe while still remaining consistent with all known experiments.

If DM is made of WIMPs, we should be able to detect it. We could in principle observe the interaction of DM particles with nuclei in underground detectors, as proposed back in 1985 [23], or we may detect the products of annihilation or decay of these particles, as first discussed almost 3 decades ago [24, 25, 4]. Although all the search strategies so far devised have failed to provide incontrovertible evidence for DM particles, today a new generation of particle astrophysics experiments is about to start, or has already started taking data. Furthermore, the Large Hadron Collider at CERN has recently started operations, and it is expected to find, or to severely constrain, the most studied extensions of the Standard Model, including SUSY.

This paper is organized as follows: in Section 2 I will review the prospects to identify Dark Matter at the LHC; in Section 3 I will discuss how to combine LHC data with the results of direct detection experiments; in Section 4 I will review the complementarity of different direct detection targets; in Section 5 I will then discuss indirect searches, and conclude.

2. Accelerator Searches

What can accelerators say about DM? A lot, probably, as the discovery of new particles would mark the beginning of a new era in particle physics and cosmology, while null searches would most probably lead to the decline of the WIMP paradigm [2]. However, even if new particles are discovered, to prove that they actually constitute the DM will be rather challenging. To illustrate this point, I will review here a specific example in the framework of a 24 parameters Minimal Supersymmetric Standard Model, recently studied in ref. [26].

The basic idea is straightforward: in case of discovery of new Physics at the LHC, the study of different kinematical variables will allow to determine the masses of several particles, with a precision that obviously depends on the properties of the specific point of the parameter space. These measurements can then be used to determine the regions of the SUSY parameter space which are consistent with such a measurement.

This can be done by applying Bayes’ theorem

\[ p(x|d) = \frac{p(d|x)p(x)}{p(d)}, \]

which updates the so-called prior probability density \( p(x) \), encapsulating the knowledge of the 24-dimensional space before taking into account the experimental constraints, \( d \), into the posterior probability function (pdf) \( p(x|d) \). The latter describes the probability density assigned to a generic 24-dimensional point \( x \) once the data have been taken into account via the likelihood function \( p(d|x) \). Furthermore, on the RHS of Eq. 1, \( p(d) \) is the Bayesian evidence which, in our case, can be dropped since it simply plays the role of a normalization constant for the posterior in this context.

The marginal pdf of a particular subset (as e.g. only one) of the 24 parameters defining \( x \) can be obtained by integrating over the remaining directions:

\[ p(x^i|d) = \int_{[1,24]\setminus\{i\}} p(x|d) dx^1...dx^{i-1}dx^{i+1}...dx^{24}. \]
Figure 1. Left: Pdf of the neutralino relic density obtained from LHC data only. Right: As in the left panel, but in the $\sigma_{\chi_{1}^0 p}^\text{SI}$ vs $\Omega_{\chi_{1}^0} h^2$ plane. The inner and outer contours enclose 68% and 95% probability regions, respectively. The best fit point is shown by the encircled black cross, while the true value is given by the yellow/red diamond. From Ref. [26].

depend on the prior assumptions. The probability distribution for any observable that is a function of the 24 SUSY parameters $f(x)$ can also be obtained since

$$p(f|d) = \delta(f - f(x))p(x|d).$$

In ref.[26] we have chosen a specific benchmark point in the MSSM parameter space, corresponding to the low-energy extrapolation of model LCC3 defined in Ref. [27]. This benchmark is representative of SUSY models in the co-annihilation region, where the lightest neutralino is almost degenerate in mass with the lightest stau. In this region, co-annihilation effects reduce the neutralino relic abundance down to values compatible with the results from the WMAP satellite [28], and therefore, the mass difference between the neutralino and the lightest stau is a fundamental parameter for the reconstruction of the relic density. It has been shown [27] that for this benchmark point LHC would be able to provide a measurement of the masses of a good part of the SUSY spectrum, including the two lightest neutralinos (see Ref. [29] for an extension of this analysis to the case of the ILC). However the masses of some particles (most notably the two heaviest neutralinos and both charginos) would not be measured. The set of measurements that we use as constraints in our analysis corresponds to that in Table 6 of Ref. [27], which assumes an integrated luminosity of 300 fb$^{-1}$. Furthermore, as pointed out in Ref. [30], the neutralino-stau mass difference can be measured with an accuracy of 20% with 10 fb$^{-1}$ luminosity in models where the squark masses are much larger than those of the lightest chargino and second-lightest neutralino, as is our case. We therefore also included a measurement of the neutralino-stau mass difference in our likelihood.

The reconstruction of the neutralino relic density is shown in Fig. 1. Consistently with previous analyses [27], multiple peaks can be observed, as a consequence of degeneracies in the SUSY parameters space that the LHC constraints are unable to break. In particular, the two observed peaks correspond to neutralinos with different composition: mostly Wino and mostly Bino, from left to right. This is a consequence of the fact that the LHC is assumed to be able to measure only the two lightest neutralino states, but not the two more massive ones or the charginos. The true value of the relic density for our benchmark point ($\Omega_{\chi_1^0} h^2 = 0.176$),
represented by a diamond in Fig. 1, is indeed inside the peak corresponding to mostly Bino dark matter. Although this value is about 60% larger than the relic abundance measured by the WMAP satellite [28], we expect our results to remain qualitatively correct for other points in the co-annihilation region leading to the correct cosmological relic abundance.

The constraints from LHC only data are also shown, in the right panel of Fig. 1, in the plane $\sigma_{\chi^{-}p}^\text{SI}$ vs $\Omega_{\tilde{\chi}_0^1}^h$, where the true value of those quantities is given by ($\Omega_{\tilde{\chi}_0^1}^h = 0.176$, $\sigma_{\chi^{-}p}^\text{SI} = 7.1 \times 10^{-8}$ pb). The leftmost region corresponds to a neutralino which has a leading Wino component, thereby displaying a smaller relic abundance, whereas the region towards larger relic abundance corresponds to Bino-like neutralinos, for which the scattering cross section is also slightly smaller.

3. Combining Accelerator Searches with Direct Detection

In view of the results of the previous section, it is important to study complementary strategies, and to investigate whether Dark Matter direct or indirect detection can actually break the strong degeneracy in the SUSY parameter space that can be seen in Fig. 1. In ref. [26] we have simulated the response of a realistic direct detection experiment to the same benchmark point studied before.

We assumed a future signal giving a WIMP detection, namely a certain number of events $N$ and a corresponding set of recoil energies $\{E_i\}_{i=1,...,N}$. The total number $N$ of simulated events is the sum of both background events (mainly interactions of detector nuclei with neutrons from surrounding rock, from residual contaminants or from spallation of cosmic muons) and recoils due to DM. For concreteness, we exemplified the method in the case of an experiment akin to the 1-ton scale SuperCDMS experiment. We simulated the differential number of background events as in Ref. [31]. Since the capability of a simulated direct detection experiment to reconstruct the DM properties (see Refs. [32, 33, 31] for more details) is worse in the case of a constant background distribution than for an exponential one, we only consider the case of energy-independent background recoil spectrum in order to be conservative. Therefore, we adopt a constant background differential spectrum $(dN_{\text{back}}/dE) = \text{const}$ which is normalized so that, when binning the spectrum in 9 bins of 10 keV width (from $E_{\text{th}} = 10$ keV to $E_{\text{max}} = 100$ keV) the number of background events in the first bin is the same as the number of DM signal events there.

The expected number of events $\lambda$ for our benchmark model and for an exposure $\epsilon = 300$ ton day is obtained by integrating the sum of the differential rate of WIMP and background events

$$\lambda = \epsilon \int_{E_{\text{th}}}^{E_{\text{max}}} \frac{dR_{\chi}}{dE} + \frac{dR_{\text{back}}}{dE} \ dE. \quad (3)$$

The dependency of the WIMP event rate on the physical quantities in the problem becomes apparent in the following parametrization [34]

$$\frac{dR_{\chi}}{dE} = c_1 R_0 e^{-E/(E_0)} F^2(E), \quad (4)$$

where

$$R_0 = \frac{\sigma_{\chi^{-}p}^\text{SI} \rho_A A^2 c^2 (m_\chi + m_p)^2}{\sqrt{\pi} m_\chi m_p^2 v_0^2}, \quad (5)$$

and

$$E_0 = \frac{2m_\chi^2 q_0^2 A m_p}{(m_\chi + A m_p)^2 c^2}. \quad (6)$$
Figure 2. Pdf of the neutralino relic density obtained with a combined analysis of LHC and direct detection data, adopting a scaling Ansatz for the local density. We show for reference the LHC-only contours of the left panel (light grey), along with the direction along which our Ansatz breaks the degeneracy (dashed lines). From Ref. [26].

Here, \( \rho_\chi \) is the local WIMP density, \( A \) is the mass number of the target nuclei (\( A = 73 \) in the case of Germanium), \( m_p \) is the proton mass, \( v_0 \) is the characteristic WIMP velocity and \( F^2(E) \) denotes the nuclear form factor. A discussion on the values of the parameters \( c_1 \) and \( c_2 \) and the functional form of \( F(E) \) can be found in Refs. [32, 33].

In order to combine the result of a direct detection experiment with LHC data, we run an additional scan of the SUSY parameter space including in the likelihood function an additional Poisson-distributed term that compares the number of events and their spectral shape predicted in each point in parameter space with the recoil spectrum. The overall background rate and its spectral shape are assumed to be known.

As shown by Eqs.3-5, the number of detected events is proportional to the product of the WIMP-proton cross section and the local DM density

\[ \lambda \propto \sigma_{\text{SI}}^{\chi-p} \rho_\chi. \]

Therefore, unless one specifies the value of \( \rho_\chi \), any information on the number of events leaves the scattering cross section practically unconstrained.

In Ref.[26] we proposed the following strategy to specify \( \rho_\chi \): we assumed that the local density of the neutralino scales with the cosmological abundance. More precisely, we proposed the following Ansatz

\[ \rho_{\chi^0} / \rho_{\text{DM}} = \Omega_{\chi^0} / \Omega_{\text{DM}}. \]

This Ansatz is strictly valid in the reasonable case where the distribution of neutralinos in large structures, and in particular in the Galaxy, traces the cosmological distribution of the DM. This is obviously true if neutralinos contribute all the DM in the Universe, but is also valid in the case where the neutralino is a subdominant component of DM, provided that DM behaves, as expected, as a cold collisionless particle. As shown below, this simple assumption is powerful tool to remove degeneracies in the parameter space.

In Fig. 2, we show the impact of adding information from direct detection experiments to the analysis based on LHC data only. These plots have been obtained by statistical posterior re-sampling of the LHC only scan, adding the relevant Ansätze and the likelihood function of a direct detection experiment as specified above. When the appropriate scaling of the local density
is applied, the aforementioned Ansatz cuts the parameter space along a direction
\[ \sigma_{\chi}^{\text{SI}} \propto \Omega^{-1} \tilde{\chi}_0^1, \]
due to the fact that for a fixed number of events \( \sigma_{\chi}^{\text{SI}} \propto \rho^{-1} \) and that under the scaling Ansatz \( \rho_{\chi} \propto \Omega_{\chi}^{-1} \). The dramatic consequences of this simple Ansatz are shown in the right-most panels of both figures. Models corresponding to a low relic density are essentially ruled out, because under the scaling Ansatz they correspond to a low local density. Given a number of observed events in direct detection searches, a low local density would require a larger scattering cross section, which is incompatible with LHC constraints. As a consequence, the parameter space region corresponding to a neutralino that is mostly Wino can now be ruled out with high confidence.

4. Combining two or more Direct Detection targets
Another interesting question is whether different detection experiments, exploiting different targets, can provide complementary information on the nature of DM particles. In ref. [35] we have discussed the reconstruction of the key phenomenological parameters of WIMPs, namely mass and scattering cross section off nuclei, in case of positive detection with one or more direct DM experiments planned for the next decade. We have in particular studied the complementarity of ton scale experiments with Xe, Ar and Ge targets, adopting experimental configurations that may realistically become available over this timescale.

| Target | \( \epsilon \) [ton x yr] | \( \eta_{\text{coll}} \) | \( \lambda_{\text{F}} \) | \( \epsilon_{\text{eff}} \) [ton x yr] | \( E_{\text{thr}} \) [keV] | \( \sigma(E) \) [keV] | background events/\( \epsilon_{\text{eff}} \) |
|--------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Xe     | 5.0            | 0.8            | 0.5            | 2.00           | 10             | Eq. 10         | \(< 1\)          |
| Ge     | 3.0            | 0.8            | 0.9            | 2.16           | 10             | Eq. 9          | \(< 1\)          |
| Ar     | 10.0           | 0.8            | 0.8            | 6.40           | 30             | Eq. 11         | \(< 1\)          |

**Table 1.** Characteristics of future direct dark matter experiments using xenon, germanium and argon as target nuclei. In all cases the level of background in the fiducial mass region is negligible for the corresponding effective exposure.

Currently, the most stringent constraints on the SI WIMP-nucleon coupling are those obtained by the CDMS [36] and XENON [37] collaborations. While XENON100 should probe the cross-section region down to \( 5 \times 10^{-45} \) cm\(^2\) with data already in hand, the XENON1T [38] detector, whose construction is scheduled to start by mid 2011, is expected to reach another order of magnitude in sensitivity improvement. To test the \( \sigma_{\chi}^{\text{SI}} \) region down to \( 10^{-47} \) cm\(^2\) \(= 10^{-11} \) pb and below, a new generation of detectors with larger WIMP target masses and ultra-low backgrounds is needed. Since we are interested in the prospects for detection in the next 5 to 10 years, we discuss new projects that can realistically be built on this time scale, adopting the most promising detection techniques, namely noble liquid time projection chambers (TPCs) and cryogenic detectors operated at mK temperatures.

In Europe, two large consortia, DARWIN [39] and EURECA [40], gathering the expertise of several groups working on existing DM experiments are funded for R&D and design studies to push noble liquid and cryogenic experiments to the multi-ton and ton scale, respectively. DARWIN is devoted to noble liquids, having as main goal the construction of a multi-ton liquid Xe (LXe) and/or liquid Ar (LAr) instrument [41], with data taking to start around 2016. The XENON, ArDM and WARP collaborations participate actively in the DARWIN project. EURECA is a design study dedicated to cryogenic dark matter detectors operated at mK temperatures. The proposed roadmap is to improve upon CRESST [42] and EDELWEISS [43] technologies and build a ton-scale detector by 2018, with a SI sensitivity of about \( 10^{-46} \) cm\(^2\) \(= 10^{-10} \) pb. The complementarity between DARWIN and EURECA is of utmost importance for dark matter direct searches since a solid, uncontroversial discovery requires
signals in distinct targets and preferentially distinct technologies. In an international context, two engineering studies (MAX [44] and LZS [45]) are funded in the US for ton to multi-ton scale LXe and LAr TPCs and the SuperCDMS/GEODM collaboration [46] plans to operate an 1.5 ton Ge cryogenic experiment at DUSEL [47]. In Japan, the XMASS experiment [48], using a total of 800 kg of liquid xenon in a single-phase detector, is under commissioning at the Kamioka underground laboratory [49], while a large single-phase liquid argon detector, DEAP-3600 [50], using 3.6 tons of LAr is under construction at SNOLab [51].

Given these developments, we will focus on the three most promising targets: Xe and Ar as examples of noble liquid detectors, and Ge as a case-study for the cryogenic technique. In the case of a Ge target, we assume an 1.5 ton detector (1 ton as fiducial target mass), 3 years of operation, an energy threshold for nuclear recoils of \( E_{\text{thr},\text{Ge}} = 10 \text{ keV} \) and an energy resolution given by

\[
\sigma_{\text{Ge}}(E) = \sqrt{(0.3)^2 + (0.06)^2} E/\text{keV} \text{ keV}. \quad (9)
\]

For a liquid Xe detector, we assume a total mass of 8 tons (5 tons in the fiducial region), 1 year of operation, an energy threshold for nuclear recoils of \( E_{\text{thr},\text{Xe}} = 10 \text{ keV} \) and an energy resolution of

\[
\sigma_{\text{Xe}}(E) = 0.6 \text{ keV} \sqrt{E/\text{keV}}. \quad (10)
\]

Finally, for a liquid Ar detector, we assume a total mass of 20 tons (10 tons in the fiducial region), 1 year of operation, an energy threshold for nuclear recoils of \( E_{\text{thr},\text{Ar}} = 30 \text{ keV} \) and an energy resolution of

\[
\sigma_{\text{Ar}}(E) = 0.7 \text{ keV} \sqrt{E/\text{keV}}. \quad (11)
\]

To calculate realistic exposures, we make the following assumptions: nuclear recoils acceptances \( A_{\text{NR}} \) of 90%, 80% and 50% for Ge, Ar and Xe, respectively, and an additional, overall cut efficiency \( \eta_{\text{cut}} \) of 80% in all cases, which for simplicity we consider to be constant in energy. We hypothesise less than one background event per given effective exposure \( \epsilon_{\text{eff}} \), which amounts to 2.16 ton\( \times \)yr in Ge, 6.4 ton\( \times \)yr in Ar and 2 ton\( \times \)yr in Xe, after allowing for all cuts.

Such an ultra-low background will be achieved by a combination of background rejection using the ratio of charge-to-light in Ar and Xe, and charge-to-phonon in Ge, the timing characteristics of raw signals, the self-shielding properties and extreme radio-purity of detector materials, as well as minimisation of exposure to cosmic rays above ground.

The described characteristics are summarised in Table 1. We note that in the following we shall consider recoil energies below 100 keV only; to increase this maximal value may add some information but the effect is likely small given the exponential nature of WIMP-induced recoiling spectra.

We start by assuming three dark matter benchmark models with \( m_\chi = 25, 50, 250 \text{ GeV} \) and \( \sigma_p^{SI} = 10^{-9} \text{ pb} \), and fix the Galactic model parameters to their fiducial values, \( \rho_0 = 0.4 \text{ GeV/cm}^3 \), \( v_0 = 230 \text{ km/s} \), \( v_{\text{esc}} = 544 \text{ km/s} \), \( k = 1 \). We then generate mock data that are in turn used to reconstrcut the posterior for the DM parameters \( m_\chi \) and \( \sigma_p^{SI} \). The left frame of Fig. 3 presents the results for the three benchmarks and for Xe, Ge and Ar separately. Contours in the figure delimit regions of joint 68% and 95% posterior probability. Several comments are in order here. First, it is evident that the Ar configuration is less constraining than Xe or Ge ones, which can be traced back to its smaller \( A \) and larger \( E_{\text{thr}} \). Moreover, it is also apparent that, while Ge is the most effective target for the benchmarks with \( m_\chi = 25, 250 \text{ GeV} \), Xe appears the best for a WIMP with \( m_\chi = 50 \text{ GeV} \) (see below for a detailed discussion). Taking into account the differences in adopted values and procedures, our results are in qualitative agreement with Ref. [52], where a study on the supersymmetrical framework was performed. However, it is worth noticing that the contours in Ref. [52] do not extend to high masses as ours for the 250 GeV
Figure 3. The joint 68% and 95% posterior probability contours in the $m_\chi - \sigma_{SI}^p$ plane for the three DM benchmarks ($m_\chi = 25, 50, 250$ GeV) with fixed astrophysical parameters. In the left frame we show the reconstruction capabilities of Xe, Ge and Ar configurations separately, whereas in the right frame the combined data sets Xe+Ge and Xe+Ge+Ar are shown.

In the right frame of Fig. 3 we show the reconstruction capabilities attained if one combines Xe and Ge data, or Xe, Ge and Ar together, again for when the Galactic model parameters are kept fixed. In this case, for $m_\chi = 25, 50$ GeV, the configuration Xe+Ar+Ge allows the extraction of the correct mass to better than $\mathcal{O}(10)$ GeV accuracy. For reference, the (marginalised) mass accuracy for different mock data sets is listed in Table 2. For $m_\chi = 250$ GeV, it is only possible to obtain a lower limit on $m_\chi$.

In the right frame of Fig. 4, the joint 68% and 95% posterior probability contours in the $m_\chi - \sigma_{SI}^p$ plane for the case in which astrophysical uncertainties are taken into account. In the left frame, the effect of marginalising over $\rho_0$, $v_0$ and all four ($\rho_0$, $v_0$, $v_{esc}$, $k$) astrophysical parameters is displayed for a Xe detector and the 50 GeV benchmark WIMP. In the right frame, the combined data sets Xe+Ge and Xe+Ge+Ar are used for the three DM benchmarks ($m_\chi = 25, 50, 250$ GeV).

### Table 2. Marginalised percent 1σ accuracy of the DM mass reconstruction for the benchmarks $m_\chi = 25, 50$ GeV. Figures between brackets refer to scans where the astrophysical parameters were marginalised over, while the other figures refer to scans with the fiducial astrophysical setup.

| Benchmark | $m_\chi = 25$ GeV | $m_\chi = 50$ GeV |
|-----------|------------------|------------------|
| Xe        | 6.5% (14.3%)     | 8.1% (21.4%)     |
| Ge        | 5.5% (16.0%)     | 7.0% (20.6%)     |
| Ar        | 12.3% (23.4%)    | 14.7% (36.5%)    |
| Xe+Ge     | 3.9% (10.9%)     | 5.2% (15.2%)     |
| Xe+Ge+Ar  | 3.6% (9.0%)      | 4.5% (10.7%)     |

benchmark – this is likely because the volume at high masses in a supersymmetrical parameter space is small.

In the right frame of Fig. 3 we show the reconstruction capabilities attained if one combines Xe and Ge data, or Xe, Ge and Ar together, again for when the Galactic model parameters are kept fixed. In this case, for $m_\chi = 25, 50$ GeV, the configuration Xe+Ar+Ge allows the extraction of the correct mass to better than $\mathcal{O}(10)$ GeV accuracy. For reference, the (marginalised) mass accuracy for different mock data sets is listed in Table 2. For $m_\chi = 250$ GeV, it is only possible to obtain a lower limit on $m_\chi$.

Fig. 4 shows the results of a more realistic analysis, that keeps into account the large
uncertainties associated with Galactic model parameters. The left frame of Fig. 4 shows the effect of varying only $\rho_0$ (dashed lines, blue surfaces), only $v_0$ (solid lines, red surfaces) and all Galactic model parameters (dotted lines, yellow surfaces) for Xe and $m_\chi = 50$ GeV. The Galactic model uncertainties are dominated by $\rho_0$ and $v_0$, and, once marginalised over, they blow up the constraints obtained with fixed Galactic model parameters. This amounts to a very significant degradation of mass (cf. Table 2) and scattering cross-section reconstruction. Inevitably, the complementarity between different targets is affected – see the right frame of Fig. 4. Still, for the 50 GeV benchmark, combining Xe, Ge and Ar data improves the mass reconstruction accuracy with respect to the Xe only case, essentially by constraining the high-mass tail.

In order to be more quantitative in assessing the usefulness of different targets and their complementarity, we use as figure of merit the inverse area enclosed by the 95% marginalised contour in the $\log_{10}(m_\chi)$ − $\log_{10}(\sigma_{SI}^p)$ plane. Fig. 5 displays this figure of merit for several cases, where we have normalised to the Ar target at $m_\chi = 250$ GeV with fixed Galactic model. Analyses with fixed Galactic model parameters are represented by empty bars, while the cases where all Galactic model parameters are marginalised over are represented by filled bars. Firstly, one can see that all three targets perform better for WIMP masses around 50 GeV than 25 or 250 GeV if the Galactic model is fixed. When astrophysical uncertainties are marginalised over, the constraining power of the experiments becomes very similar for benchmark WIMP masses of 25 and 50 GeV. Secondly, Fig. 5 also confirms what was already apparent from Fig. 3: Ge is the best target for $m_\chi = 25$, 250 GeV (although by a narrow margin), whereas Xe appears the most effective for a 50 GeV WIMP (again, by a narrow margin). Furthermore, the inclusion of uncertainties drastically reduces the amount of information one can extract from the data: the filled bars are systematically below the empty ones. Now, astrophysical uncertainties affect the complementarity between different targets in a non-trivial way. To understand this point, let us focus on the two rightmost bars for each benchmark in Fig. 5, corresponding to the data sets Xe+Ge and Xe+Ge+Ar. For instance, in the case of a 250 GeV WIMP, astrophysical uncertainties seem to reduce target complementarity: adding Ar to Xe+Ge leads to a significant increase in the figure of merit for analyses with fixed astrophysics (empty bars) but has a
negligible effect for analyses with varying astrophysical parameters (filled bars). For low mass benchmarks, the effect of combining two (Xe+Ge) or three targets (Xe+Ge+Ar) is to increase the figure of merit by about a factor of 2 compared to Xe alone or Ge alone, almost independently of whether the astrophysical parameters are fixed or marginalised over. However, the overall information gain on the Dark Matter parameters (for light WIMPs) is reduced by a factor $\sim 10$ if astrophysical uncertainties are taken into account, compared to the case where the Galactic model is fixed.

5. Indirect detection

Indirect detection consists in the search for the annihilation or decay products of DM particles, such as photons, anti-matter and neutrinos. WIMPs in fact are expected to annihilate efficiently in regions where they accumulate, such as the center of galactic halos, or substructures such as dwarf galaxies, since the annihilation rate depends on the number density squared. Once they annihilate, they produce secondary particles, such as quarks and gauge bosons, which subsequently fragment and decay in the aforementioned final states. The typical energy of these final states is about a tenth of the DM particle mass, so we can search indirectly for DM by looking for an excess of photons, anti-matter or neutrinos in astrophysical data at energies between 1 GeV and 10 TeV [4].

Although in principle interesting, obtaining convincing evidence from astrophysical observations has proven a very difficult task. It is in fact easy to fit almost any excess in the measured energy spectrum of photons or anti-matter, at any energy, in terms of DM particles with suitable properties. One simply has to follow three easy steps: i) adjust the normalization of the flux by changing the distribution of DM particles and their annihilation cross section ii) choose a WIMP mass that provides the correct energy scale iii) fit the spectral features by choosing an appropriate annihilation channel and, in the case of anti-matter, by tuning the propagation parameters.

In practice, one has enough freedom to fit almost any astrophysical observation, and in fact features in the data of many experiments of the last 5-10 years, have been tentatively interpreted in terms of different DM candidates, sometimes even at the cost of making unrealistic assumptions on the nature and distribution of DM. The most recent example is the rise in the energy spectrum of the positron ratio measured by PAMELA above 10 GeV [53]. The standard WIMP model (i.e. a particle with a mass in the $10^2 - 10^3$ GeV range and a thermal cross section, $\sigma v \sim 10^{-26}$ cm$^3$ s$^{-1}$) can hardly account for this feature, so new ad-hoc candidates have been proposed: particles with a very large annihilation cross section (high enough to match the normalization of the positron ratio, but not too much, in order to avoid cosmological constraints [54, 55]), annihilating only to leptons (to evade anti-protons constraints [56]), and with a density profile shallower than what suggested by numerical simulations (to evade gamma-ray constraints from the Galactic center [57]). There is therefore a possible combination of parameters that can be made compatible with all observations, but this is certainly not enough to claim discovery of Dark Matter, for there are less exotic astrophysical sources that can account for the same feature without invoking new particles with ad-hoc properties.

We have shown that among the most stringent constraints on the properties of DM particle, and in particular on the DM interpretation of the PAMELA data, the most robust are provided by cosmic microwave background (CMB) observations [54, 55], since they do not depend on poorly known quantities such as the DM profile at the Galactic center, or the details of the propagation of anti-matter in the Galaxy.

Fortunately, there are actually a number of astrophysical observations that might lead to convincing evidence, in the sense that they could be explained only in terms of Dark Matter, while being incompatible with a standard astrophysical interpretation. A typical example of smoking-gun evidence is the observation of a high-energy gamma-ray line, that would point
directly to the existence of new particles annihilating directly to photons. In fact, if WIMPs do
not produce photons through the fragmentation and decay of secondary particles, but directly,
the photons produced in the annihilation will be mono-energetic, thus producing a line in the
gamma-ray spectrum at an energy equal to the mass of the Dark Matter particle. The Fermi LAT
satellite has however put stringent constraints on the possibility to observe lines [58], excluding
annihilation cross section to photons higher than the thermal cross section, and we can expect
an improvement in sensitivity of one order of magnitude at most over the next decade (at least
in the energy range where the sensitivity is limited by statistics, and not by the background, in
which case the sensitivity scales with the square root of time).

Another very clean signature of Dark Matter annihilations would be the observation of high-
energy neutrinos from the center of the Sun. Solar neutrinos produced in nuclear reactions have
in fact energies in the MeV range, so the observation of $10^2$ - $10^4$ GeV neutrinos would require an
explanation in terms of new physics, and the well studied process of capture and annihilation of
Dark Matter particles in the Sun would provide it. The problem is that the neutrino telescope
IceCube, currently under construction at the South Pole, so far has not found any evidence
for an excess of neutrinos from the Sun, and in the next 5 years, the experiment will improve
its sensitivity only by a factor of $\sim 5$, and extend the threshold down to 50 GeV, with the
construction of a more densely instrumented portion of detector, called DeepCore [59]. Even
with this technical improvements and longer exposure, most of the Supersymmetry parameter
space will remain inaccessible, and the same holds true for the so called Kaluza–Klein Dark
Matter in theory with universal extra-dimensions.

Other strategies may provide useful hints, such as the multi-wavelength approach, that
consists in the combined analysis of astrophysical spectra at different wavelengths, with the
aim of observing e.g. the Synchrotron and Inverse Compton emission produced by secondary
electrons produced along with gamma-rays by Dark Matter annihilations [60]. Or the study
of the angular power spectrum of gamma-ray anisotropies [61], that may allow to identify a
Dark Matter contribution to the diffuse gamma-ray background. But even in case of detection,
it would probably require a long time before these observations are considered as proof of the
existence of Dark Matter, because one would have to exclude an astrophysical origin of the
signal. Fortunately, although indirect searches may appear to be not particularly suited to
provide incontrovertible evidence for Dark Matter, they have the big advantage of not requiring
dedicated experiments, and that some theoretical models are indeed within the reach of current
and upcoming experiments in the next 5–10 years. In absence of these (admittedly optimistic)
smoking-gun observations, a convincing case for Dark Matter can be made only in case of
successful searches at accelerators or direct detection experiments, in which case indirect searches
may still provide useful information on the distribution of Dark Matter.

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D. Cerdeno, M. Fornasa, M. Pato, R. Ruiz de Austri, L. Strigari, R. Trotta in Refs. [2, 26, 35].

[1] Particle Dark Matter: Observations, Models and Searches, ed. G. Bertone, 2010, Cambridge University Press
[2] G. Bertone, Nature 468 (2010) 389-393. [arXiv:1011.3532 [astro-ph.CO]].
[3] Bergstrom L., Rept. Prog. Phys. 63, 793-841 [arXiv:hep-ph/0002126] (2000)
[4] G. Bertone, D. Hooper and J. Silk, Phys. Rept. 405, 279 (2005) [arXiv:hep-ph/0404175].
[5] C. Munoz, Int. J. Mod. Phys. A19, 3093-3170 (2004). [hep-ph/0309346].
[6] D. Hooper, S. Profumo, Phys. Rept. 453, 29-115 (2007). [hep-ph/0701197].
[7] Komatsu E. et al., arXiv:1001.4538 [astro-ph.CO]. (2010)
[8] Diemand J. and Moore B., “Simulations of CDM haloes,” in Particle Dark Matter: Observations, Models
and Searches, ed. G. Bertone, p. 14-37, Cambridge University Press (2010)
[9] Mellier Y., “Gravitational lensing and dark matter,” in Particle Dark Matter: Observations, Models and
Searches, ed. G. Bertone, p.56-82, Cambridge University Press (2010)
[10] Catena R. and Ullio P., JCAP 1008 004 arXiv:0907.0018 [astro-ph.CO]. (2010)
[11] Pato M., Agertz O., Bertone G., Moore B. and Teyssier R., Phys. Rev. D 82 023531, arXiv:1006.1322 [astro-ph.HE] (2010)
[12] P. Salucci, F. Nesti, G. Gentile et al., Astron. Astrophys. 523 (2010) A83. [arXiv:1003.3101 [astro-ph.GA]].
[13] L. E. Strigari, R. Trotta, JCAP 0911 (2009) 019. [arXiv:0906.5361 [astro-ph.HE]].
[14] Taoso M., Bertone G. and Masiero A., JCAP 0803, 022 [arXiv:0711.4996 [astro-ph]].
[15] Sikivie P., “Axions,” in Particle Dark Matter: Observations, Models and Searches, ed. G. Bertone, p. 204-227, Cambridge University Press (2010)
[16] Visinelli L. and Gondolo P., Phys. Rev. D 80, 035024 [arXiv:0903.4377 [astro-ph.CO]]. (2009)
[17] Shaposhnikov M., “Sterile Neutrinos,” in Particle Dark Matter: Observations, Models and Searches, ed. G. Bertone, p. 228-248, Cambridge University Press (2010)
[18] Boyarsky A., Ruchayskiy O. and Shaposhnikov M., Ann. Rev. Nucl. Part. Sci. 59, 191-214 [arXiv:0901.0011 [hep-ph]]. (2009)
[19] Goldberg H., Phys. Rev. Lett. 50, 1419-1422 (1983) [Erratum-ibid. 103, 099905 (2009)].
[20] Ellis J. R., Hagelin J. S., Nanopoulos D. V., Olive K. A. and Srednicki M., Nucl. Phys. B 238 453-476 (1984)
[21] Jungman G. , Kamionkowski M. and Griest K., Phys. Rept. 267 195-376 [arXiv:hep-ph/9506380] (1996)
[22] Silk J. and Witten E., Phys. Rev., D31:3059 (1985).
[23] Goodman M.W. and Witten E., Phys. Rev., D31:3059 (1985)
[24] Shaposhnikov M., “Sterile Neutrinos,” in Particle Dark Matter: Observations, Models and Searches, ed. G. Bertone, p. 228-248, Cambridge University Press (2010)
[25] E. Aprile et al. (XENON100 Collaboration), Phys. Rev. Lett. 105, 131302 (2010) [arXiv:1005.0380 [astro-ph.CO]].
[26] E. Aprile et al. (XENON1T Collaboration), JCAP 0501, 005 (2005) 182 [arXiv:hep-ph/0503165].
[27] E. Komatsu et al. [WMAP Collaboration], Astrophys. J. Suppl. 180 (2009) 330 [arXiv:0803.0547 [astro-ph]].
[28] V. Khotilovich, R. L. Arnovitt, B. Dutta and T. Kamon, Phys. Lett. B 618 (2005) 182 [arXiv:hep-ph/0503165].

http://darwin.physik.uzh.ch/
http://www.eureca.ox.ac.uk/
http://www.cresst.de/
http://edelweiss.in2p3.fr/
http://www.fnal.gov/pub/max/index.html
http://www.ixa.stanford.edu, JCAP 0301, 007 (2008) [arXiv:0703165 [astro-ph]].
http://www.iri.titech.ac.jp/
Hiroyuki Sekiya (for the XMASS collaboration), in proceedings of the 1st International Workshop towards the Giant Liquid Argon Charge Imaging Experiment, arXiv:1006.2023 (2010)
http://www-sk.icrr.u-tokyo.ac.jp/index-e.html
http://deapclean.org/
http://www.snolab.ca/
http://deapclean.org/
http://www.mnolab.ca/
Y. Akrami, C. Savage, P. Scott, J. Conrad and J. Edsjo, arXiv:1011.4318 [astro-ph.CO].
[56] Cirelli M., Kadastik M., Raidal M. and Strumia A., “Model-independent implications of the $e^+$, $e^-$, anti-proton cosmic ray spectra on properties of Dark Matter,” Nucl. Phys. B 813, 1-21 [arXiv:0809.2409 [hep-ph]]. (2009)

[57] Bertone G., Cirelli M. , Strumia A. and Taoso M., “Gamma-ray and radio tests of the e+e- excess from DM annihilations,” JCAP 0903, 009 [arXiv:0811.3744 [astro-ph]]. (2009)

[58] Abdo A. A. et al., “Fermi LAT Search for Photon Lines from 30 to 200 GeV and Dark Matter Implications,” Phys. Rev. Lett. 104, 091302 [arXiv:1001.4836 [astro-ph.HE]]. (2010)

[59] Halzen F. and Hooper D., “The Indirect Search for Dark Matter with IceCube,” New J. Phys. 11 105019 [arXiv:0910.4513 [astro-ph.HE]]. (2009)

[60] Profumo S. and Ullio P., “Multi-wavelength Searches for Particle Dark Matter,” arXiv:1001.4086 [astro-ph.HE], in Particle Dark Matter: Observations, Models and Searches, ed. G. Bertone, p. 547-564, Cambridge University Press (2010)

[61] Ando S. and Komatsu E., “Anisotropy of the cosmic gamma-ray background from dark matter Phys. Rev. D 73 023521 [arXiv:astro-ph/0512217]. (2006)