Status of indirect dark matter detection

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Abstract. Indirect astrophysical channels (such as gamma rays, neutrinos, and cosmic ray antimatter) are a cornerstone in the dark matter particle identification program. A review of the present constraints is presented, together with some perspectives for the near future: we argue that the approach of "fitting any spectral feature to a dark matter model" is unlikely to lead to a convincing indirect detection of dark matter. Rather—if the WIMP paradigm for dark matter is correct—guidance from collider and direct detection programs is expected to allow soon for more fruitful *a priori* searches of correlated signatures in many indirect channels.

1. Introduction

The known matter (be it in visible form or not) cannot account but for a small fraction of the gravitational attraction binding together the largest structures of the universe, from galaxies to clusters and beyond. This is one of the most surprising results of 20th century astrophysics, that required evidence to be collected over many decades in order to be fully appreciated: from the first observations of the Coma cluster by Zwicky (summarized in [1]) to the puzzlingly flat rotation curves of spiral galaxies studied by V. Rubin and collaborators (see [2] for a review); from the indirect evidence from cosmology (like the baryometric measurement first obtained via primordial nucleosynthesis and the depth of the potential fluctuations inferred from CMB) to the spectacular recent inferences from colliding clusters thanks to lensing (a short account of most of these observations has been given in [3]). Yet, all these detections are gravitational: the universality of gravity prevents us to identify the particle physics nature of this (or these) "new species", dubbed dark matter (DM). A re-discovery of DM via other channels is clearly needed for that purpose. In this framework, indirect detection (ID) of DM means looking for consequences of DM interactions elsewhere than in the Lab: namely via putative decays, annihilations, and energy transfer to baryons. The motivations of this strategy are clear: i) It is an obvious thing to do, since DM has been seen only elsewhere than in the Lab, after all! ii) These features may imply a further impact of DM on cosmology or astrophysics, via non-gravitational effects on the baryonic fluids. iii) It provides an additional handle on properties one cannot probe otherwise in the Lab. That said, it is also worth recalling that

- The presence of indirect signatures is by no means guaranteed, rather is model-dependent.
- It need not be an electroweak (EW) scale signature, neither necessarily an annihilation one. Notable exceptions exist, two examples of which are keV mass scale sterile neutrinos possibly emitting a X-ray line via decay (see [4] for a review), or proposed annihilation signals of MeV DM impacting wildly different systems, from the Galactic Bulge soft gamma-ray emission [5] to indirect effects in primordial nucleosynthesis [6].

- There is no *astrophysical or cosmological evidence* for the electroweak scale being the right one for explaining the DM problem. Rather, it is a particle physics theory prejudice.

With these caveats in mind, if is fair to say that the most popular class of DM candidates are Weakly Interacting Massive Particles (WIMPs), based on the following three main arguments:

- The "WIMP miracle", the intriguing coincidence that a thermal relic with electroweak coupling and mass scale matches the cosmological measurement, $\Omega_{DM} \approx 0.25$, within an order of magnitude or so.
- To ease agreement with EW observables (as well as to fulfill constraints such as the lower limit on the proton lifetime) in beyond the standard model (BSM) scenarios, model-builders often require some discrete symmetry differentiating SM particles from BSM ones, like R-parity in SUSY, K-parity in Extra-Dimensional modes or T-parity in Little Higgs. In turn, this implies the stability of the lightest particle of the BSM sector. More generally, this kind of arguments together with the first point above has brought some confidence that, whatever the BSM physics at the EW scale may be, it could be related to DM.
- Last but not least, EW-scale candidates have a rich phenomenology, allowing for more creativity from the model-building perspective, together with more detection strategies via collider, direct, and indirect techniques.

In the rest of this mini-review I will thus concentrate on WIMP-like candidates and signatures, but it is important to keep in mind other possibilities (among which some well motivated ones are axions, superheavy DM, and superWIMPs; see [7] for a review). Some of these have independent motivations and/or peculiar signatures, requiring ad hoc searches: at TAUP 2011 an example has been illustrated in the talk by M. Grefe on indirect searches for gravitino dark matter. When restricting oneself to WIMP candidates, the basic strategy can be summarized as follows:

- To demonstrate that astrophysical DM is made of particles: locally, via direct detection (DD) in underground labs; remotely, via ID.
- Possibly, create DM candidates in the controlled environments of accelerators, most notably the LHC.
- Find consistency between properties of the two classes of particles. Ideally, we would like to be able to calculate the relic abundance and DD and ID signatures on the basis of collider data, testing the link with cosmology and production mechanism.

For ID, one ca use different particles as probes, as reviewed in the following Secs. 2, 3, and 4. Section 5 is instead devoted to a discussion, and Sec. 6 to the conclusions. The emphasis is given to recent results and/or results mentioned at the TAUP 2011 conference.

2. Gamma Rays
Gamma rays have several advantages as DM discovery tools: they retain directionality, so they map the DM distribution (squared, for annihilations) in the halo of the Milky Way as well as any other (sub)structures, either of our Galaxy or of the extragalactic sky. Another good feature is that gamma rays are generically found as byproducts of the DM, via the fragmentations/decays of the different SM particles created in the annihilation/decay process.

Theoretical predictions of spectra can be obtained via standard tools used in particle physics like PYTHIA, or via appropriate fittings/parameterizations to these results, see for example [8]. On the other hand, the photon line final states are suppressed by the very request of the DM being "dark": they must proceed trough loops and their intensity results both suppressed and model-dependent. This channel will be briefly commented upon in Sec. 5. As long as "vanilla WIMPs" are concerned, only a few qualitatively different spectra can be expected (e.g., τ leptons vs. softer quark-like ones) and quasi-universal spectra can be thus used as templates for searches.

Concerning the angular distribution of the signal, at least for the prompt photons (see Sec. 4.3 for a comment on non-prompt ones) it is completely specified by the DM distribution: for some expectations on amplitudes and anisotropies of the signal see e.g. [11]. Of course, the lack of detailed knowledge of the DM distribution translates into an uncertainty in the signal angular shape and normalization, which is particular important for the Galactic Center region and the extragalactic signal.

Perhaps most important, the signal prediction is often less troublesome than the presence of a significant background of astrophysical nature: the gamma-ray sky revealed by space telescopes like Fermi or ground-based Atmospheric Cherenkov Telescopes (ACTs) like HESS, MAGIC or VERITAS looks nothing like DM expectations, neither in spectra nor morphology. Not only backgrounds are important, but their nature and characteristics are revealed step by step, with the increased sensitivity of the instruments. The challenge might be compared with looking for BSM physics in LHC data while having only vague ideas of what the QCD and EW backgrounds look like. To different degrees of complexity, this is the basic problem of most ID searches. However, photons keep at least the advantage of directionality, so the search strategies can be "customized" for different targets, as illustrated in the following subsections.

2.1. Dwarf Galaxies

These targets, which are known satellites of the Milky Way, are relatively rich in DM with respect to baryons, and are usually assumed to have no intrinsic background [1]. The dominating foreground uncertainty then comes from the uncertainty in the diffuse galactic background estimate and is of lesser concern. On the other hand the signal depends on the estimated distance and volume average of the squared DM density, and it is only as robust as the latter estimates are. Recent bounds from a *stacked* analysis by the Fermi collaboration—which rely on their own astrophysical data analysis for the dwarfs—nominally exclude "generic thermal" s-wave relic WIMPs annihilating into b-quarks with mass up to 27 GeV, and into τ's up to 37 GeV: see the Fermi-LAT collaboration analysis in [12] and the independent one in [13]. While ACTs have sensitivity to higher DM mass values and have considered dwarf galaxies as interesting targets, the bounds obtained are rather weak, orders of magnitude away from expectations. The recent MAGIC bounds from Segue 1 [14], of HESS from globular clusters M15 and NGC 6388 [15] or the 2010 ones by VERITAS [16] should give a feeling on how far the sensitivity is from theoretically interesting values of parameters.

2.2. Diffuse Gamma-ray Flux

The signal from the smooth Galactic DM halo constitutes a lower limit to the expected one, since it can be enhanced in case of clumpiness. Also, the signal is relatively large in terms of absolute numbers of photons. The major drawback is that the astrophysical background is also large and actually dominating. Basically, the strength of the constraints depend on how one deals with this background: one can take the hyper-conservative approach of using the observed number of photons and assume that the DM signal does not overshoot it, see e.g. [17]. Or one can vary the foregrounds within reasonable ranges of the parameters and use conservative assumptions to derive the bounds, as done in [18]. An independent analysis was performed in [19] based on the assumption of approximate cylindrical symmetry of signal (in galactic coordinates) and uncorrelated pixels, obtaining results essentially in agreement with [18]. It is also worth noting that the optimal strategy maximizing the signal/background is actually dependent not only on

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[1] Needless to say, this assumption is going to break down at some level. For example, it is known that dwarfs can harbour globular clusters; based on Fermi data [9], globular clusters often host millisecond pulsars which are gamma-emitters. For the promising (nearby, DM-rich) Sagittarius dwarf, the presence of the globular cluster M54 alone makes one expect an astrophysical VHE signal two orders of magnitude larger than a typical thermal WIMPs one, and detectable with the future CTA [10].

the level of foregrounds, but also on the assumed profile of the inner halo (see the simplified example discussed in [20]).

At high Galactic latitutes, it is expected that both the Galactic Halo and the extragalactic flux contribute to the signal: actually, this is known to be the case at least for the background. In general, despite the relevant statistics, in this case it is even trickier to disentangle the signal from the numerous astrophysical foregrounds; a recent analysis has been presented by F. Donato at this conference (see [21]), while new strategies have been discussed e.g. in [22, 23]. Some effort is also going into refining and simplifying the theoretical predictions of the extragalactic signal, see for example [24].

2.3. Inner Galaxy

The Galactic Center region has been recognized long ago as a very promising target, given its potentially very high statistics and relatively narrow angular extent, which is suitable for detection also at ACTs [25]. Needless to say, it is subject to the usual problems in the foreground estimates, which involve in this case both discrete sources (point-like or extended) and the diffuse flux, see e.g. [26]. In general, in order to reduce the impact of the complex astrophysics at the Galactic Center, it is often more robust to look away from it to obtain reliable bounds. This strategy was followed for example to obtain the HESS bound in [27]: a *signal region* close to the Galactic Center but as much as possible free from backgrounds was selected; then a similar shape region where signal is expected to be smaller was selected for background estimate. The resulting analysis leads to the most stringent bound on DM from ACTs I am aware of, yet still one order of magnitude or larger away from expectations. Additionally, it is a halo-model dependent constraint, relaxing considerably for cored halo profiles.

Compared to early estimates based on pre-Fermi knowledge [28, 29], Fermi-LAT data have revealed a more complex structure of sources at the Galactic Center: intriguing "excesses" should thus be weighted against poorly understood backgrounds, see e.g. [30, 31, 32]. The Fermi-LAT team analysis is in fact still in progress: for preliminary results see [33].

3. Neutrinos

The same kind of scattering reactions probed in direct detection techniques may be responsible for the capture of halo DM particles by the Sun (or, to a minor extent, the Earth): after sinking to the core of the Sun, DM particles can annihilate at a significant rate, especially if equilibrium between capture and annihilation is reached. At steady state, the annihilation rate depends "almost exactly" (but see [34]) on the same product of local density and cross section entering DD experiments. Since the Sun is mostly made of protons, bounds on spin-dependent cross-sections are comparatively stronger than those on spin-independent ones, where terrestrial detectors can exploit the coherent scattering on massive target nuclei. Recently, Ref. [35] used Super-Kamiokande upper limits on additional flux on top of atmospheric neutrinos to probe light DM (order 10 GeV or less), of interest on the light of some direct detection results (DAMA/LIBRA, CoGeNT, CRESST). The analysis excludes for example spin-dependent interpretations of these data in terms of either s-wave or p-wave thermal relics, basically independent of the SM final state. Even for spin-independent interpretations significant tensions exist (especially for s-wave annihilation), unless the annihilation proceeds into light quark species [35, 36].

On the other hand, bigger (but higher-threshold) neutrino telescopes under water or ice have sensitivity to heavier DM candidates: recent bounds in interesting parts of parameter space have been derived by IceCube, see e.g. [37] or the contribution of M. Danninger. Encouraging progress has also been reported by ANTARES (see contribution to this conference by Vincent Bertin). Some less constraining IceCube bounds from the Inner Galaxy have been recently reported in [38].

4. Charged Particles

Indirect DM searches via cosmic rays has been considered long ago, see e.g. [39]. Yet, this method is slightly more indirect since it relies not only on DM physics (like mass and cross sections) and astrophysics (halo distributions), but also on the plasma astrophysics processes which regulate the diffusive propagation in the Galaxy (see [40, 41, 42] for introductions to this topic). In general, antimatter channels are preferred with respect to matter CRs due to the lower astrophysical background expected (essentially secondaries from inelastic collisions in the interstellar medium). Here we briefly review antiproton and lepton constraints. We mention that $e^{\pm}$ can also produce synchroton signals in the Galactic magnetic field; this topic was covered in the talks by R. Lineros and M. Taoso, see also [43] and [44].

4.1. Antiproton Flux

Antiproton constraints are particularly interesting for relatively light DM candidates. For example, recent analyses [45, 46] disfavour an s-wave annihilating thermal relic interpretation of some direct detection "signals". On the other hand, constraints on heavier DM candidates are less stringent. Yet, some of these are interesting in the context of models with high annihilation cross sections, such as some of those invoked a few years ago to explain the PAMELA positron fraction. In both cases, antiproton constraints tend to corroborate similar or stronger constraints coming from gamma ray results.

4.2. Electron and Positron Fluxes

Charged leptons are a relatively worse channel for indirect DM searches, at least as a discovery tool: Compared to antiprotons, for example, they are more sensitive to source and propagation inhomogeneities as well as to energy losses; also, the signal has to compete with many more potential astrophysical backgrounds: there are many more leptonic accelerator candidates than hadronic ones! For a recent review of astrophysical interpretations of positron data, see [47]. To use an analogy, it would be like starting to look for new physics at LHC in soft jets, where non-perturbative QCD plays an important role. Compared with the excitement of the past few years, at this conference there has been relatively little discussion of these topics. One exception has been the talk by E. Borriello, based on [48], on DM vs. astrophysical diagnostics via anisotropy constraints. Not surprisingly, a general trend in current research is focusing on possible ways to discriminate between DM signals and astrophysical foregrounds. One the other hand, recent results by Fermi [49] allowed for an indirect measurement of the separate electron and positron flux thanks to the geomagnetic "Earth shadow". They confirm the previous trend of rising positron fraction indicated by PAMELA [50] up to $E \simeq 200$ GeV, thus requiring higher minimum masses for DM to fit the rise. Since existing bounds are relatively stronger at higher DM masses, the parameter space for DM interpretations of positron data is narrowing down even further.

4.3. Other constraints and recent progress in phenomenology

Some activity has also been developed to investigate the impact of DM in a cosmological context. In particular, we mention here that energetic byproducts of DM annihilating during the *Dark Ages* (redshift $z \simeq 100$–1000) can ionize baryons. In turn, the CMB probes this phenomenon in particular via the optical depth τ. Detailed analyses such as [51] indicate that particles in the 5–10 GeV mass range annihilating into $\mu^{\pm}$ or $e^{\pm}$ can be constrained at the level of the thermal relic cross section already with present data. The forecast for Planck looks even more promising for light DM candidates.

Recent phenomenologically inspired model-building has also focused on heavy ($m \gtrsim$ TeV) "leptophilic" DM candidates. Indirect signatures of these candidates (for example gammas) are mostly observable at $E \ll m$. In this range, it is important to consider: i) *tertiary*

signatures, like inverse Compton photons from the scattering on interstellar light of e$^{\pm}$ originating from DM; ii) multi-body final states, from sub-threshold virtual states [52, 53] or W,Z-strahlung [54, 55, 56, 57, 58, 59, 60, 61, 62]. A talk on electroweak effects has been given at this conference by A. De Simone.

5. A paradigm shift: towards indirect dark matter detection perspectives

When trying to move from the *constraint phase* to the *detection phase*, one immediately faces the trouble of identifying *reliably* genuine signatures of DM as opposed to astrophysical foregrounds. A first strategy is to look for (what are believed to be) *unique* signatures of DM, such as non-negligible fluxes of antideuterons in cosmic rays at relatively low energy, high energy neutrinos from the Sun or Earth Core, or gamma-ray lines. A discovery via these means, while possible, requires a great dose of luck for typical WIMP parameters: the signals are expected to be small and in some cases very special detector requirements are needed (as the mass/charge resolution in the case of antideuterons, or the size of neutrino detectors). Recently, Fermi-LAT data have allowed to derive new bounds on gamma-ray lines [63, 64], which are nonetheless orders of magnitude away from expectations. Despite some hope to investigate conceptually similar but more promising spectral features at future ACTs (see talk by C. Weniger and Ref. [65]), it is fair to say that not much could be learned from a negative result. These channels cannot be used as a crucial test for the WIMP paradigm.

What I believe to be a poor strategy is instead to ask oneself if a CR feature can be fitted with some DM model. While popular in the current literature, this approach can most likely lead to fool oneself. In fact, most DM models have enough free parameters to control: a) spectral shape (by adjusting the final state and/or propagation parameters) b) endpoint/energy scale (by adjusting the mass) c) normalization (by adjusting the mass, cross section or decay rate, as well as DM profile, the latter also controlling angular shape.) It is more likely than not that one will be able to find a reasonably good fit! The real issues for "claiming indirect detection" are however:

i) To find an explanation of *many phenomena* with particle physics *motivated models*.

ii) To predict indirect detection features *which cannot be understood by known astrophysics*.

iii) To have predictive links with direct search or collider signatures.

Needless to say, the number of key free parameters should be relatively small.

By looking at the near past, one immediately realizes that the DM community has probably been fooling itself in an ID several times: this is the case of the Galactic Center gamma-ray emission [66, 67], the 511 keV emission from positron annihilation in the Galaxy (for a review see [68]), or the e^{+} fraction in cosmic rays [50], which have all been interpreted as possible if not likely DM signals. Later on, more mundane (but still astrophysically exciting!) origins have gained more and more plausibility. So, *what lesson should we draw?*

My opinion is that, barring a few hints still debated, most indirect signatures told us that *DM indirect signals are not dominant*, rather at the level or even well below astrophysical foregrounds, some of which have been discovered and investigated along the way. Experiments like AMS-02 [69] and ongoing as well as forthcoming gamma-ray detectors will provide further checks of the internal consistency of simple models of the cosmic rays. This field is being re-defined by high-quality data, extending over a larger dynamical range. A few years ago, the attitude was that the major uncertainties in ID was due to interstellar medium and propagation parameters, as well as nuclear physics input. A larger community now appreciates that a more challenging limitation to overcome is the lack of detailed knowledge of the sources. Fortunately for us, this is a wonderful time to do high-energy astrophysics, with plenty of data and excellent perspectives!

6. Conclusions

In summary, astrophysical and cosmological indirect probes have had a major impact on particle physics: they have told us that BSM physics does exist and contributes significantly to shape the Universe we live in!

On the other hand, they do not tell us *the scale* at which BSM physics should appear. More and more indirect detection channels are limited by systematic errors in the knowledge of foregrounds rather than by statistical errors. As a consequence, until a better understanding of high energy astrophysics will be achieved, blind searches for DM will become more and more challenging. To a large extent, it is likely that if the WIMP paradigm is correct, collider searches will collect the first unambiguous signals for BSM physics at the electroweak scale, perhaps accompanied by further evidence of DM at direct detectors underground. With the LHC finally up and running, it is advisable to go back to the standard, healthy practice in particle physics, when experimental results were paving the way to theoretical interpretations, which in turn would predict also independent and indirect signatures. We can just look forward to repeating this path to discovery, whose advantages for indirect detections cannot be underestimated: knowing what and where to look for DM would avoid the "look elsewhere effect" and increase the credibility of a signal hint. In fact, it should be appreciated that if a signal is found in other channels (collider/direct detection), we would still need ID:

- To confirm that whatever we find in the Lab is the same "dark stuff" responsible for astrophysical and cosmological observations.
- To access particle information not otherwise available in the Lab (annihilation cross section or decay time, for example).
- To infer cosmological properties of DM (e.g. power spectrum of DM at very small scales) not easily accessible otherwise.

In the meanwhile, ongoing or near future astrophysical observations will help gaining more sensitivity and precision as well as better understanding of astrophysical sources and propagation parameters. By the next edition of TAUP, we might be talking of the *recent detection of DM* or, perhaps, should start contemplating the need for a new paradigm in this fascinating quest.

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