Indirect dark matter searches in gamma and cosmic rays

Jan Conrad¹ and Olaf Reimer²*

Dark matter candidates such as weakly interacting massive particles are predicted to annihilate or decay into Standard Model particles, leaving behind distinctive signatures in gamma rays, neutrinos, positrons, antiprotons, or even antinuclei. Indirect dark matter searches, and in particular those based on gamma-ray observations and cosmic-ray measurements, could detect such signatures. Here we review the strengths and limitations of this approach and look into the future of indirect dark matter searches.

Evidence for particle dark matter is so far circumstantial. Cosmological observations on different scales (see for instance ref. 1) are most convincingly explained by introducing new, as yet unknown, particles whose existence at best also solves other conundrums in modern physics. Proposed particle candidates for dark matter span more than 60 orders of magnitude in cross-section (with Standard Model particles) and about 45 orders of magnitude in mass (Fig. 1). Obviously, no single experimental technique can cover such a parameter range. The most popular candidate, the very focus of this article, is a particle type that is weakly interacting, but much more massive than a neutrino (weakly interacting massive particle, or WIMP). A very plausible hypothesis for the production of dark matter is that it consists of thermal relics of the Big Bang (much like the photons of the cosmic microwave background). Since the annihilation of dark matter particles into Standard Model particles controls the abundances in the Universe, principally one expects a firm connection between their ability to interact—expressed by the velocity-averaged annihilation cross-section \(\langle \sigma v \rangle\), which for brevity we will simply refer to as annihilation cross-section—and the cosmologically relevant properties or observables. In particular, the abundance of thermal relics can be accurately calculated and yield, with two simple assumptions on interaction strength and mass for a WIMP, an abundance that is close to the one that is very accurately measured by cosmological observations. Sometimes this coincidence is popularized as the ‘WIMP miracle’. As the abundance is regulated by the already mentioned annihilation cross-section, requiring that the relics provide the entire observed dark matter provides a benchmark for indirect detection at about \(3 \times 10^{-26} \text{ cm}^2 \text{ s}^{-1}\).

An additional feature of WIMPs is that particle theories beyond the Standard Model, invoked for a different reason than dark matter, often generically include a WIMP. In particular, supersymmetry, which roughly doubles the number of particles in the Standard Model, provides such a particle, referred to as neutralino. Self-annihilation is consequently a viable scenario to be investigated by indirect dark matter search techniques.

Apart from establishing the particle nature of dark matter, an unambiguous indirect detection of dark matter annihilation will also yield information about its microscopic properties. In particular, detection would allow for the estimation of the annihilation cross-section (assuming known dark matter velocity and density distribution) and the dark matter mass. In the absence of a clear signal, constraints on these quantities can still be obtained.

To a lesser extent, but still of importance, the signature in gamma- and cosmic-ray observations is determined by the composition of Standard Model particles that the WIMP annihilate. Most often, single-annihilation channels are assumed (for instance, annihilation into b-quark pairs), mainly motivated by the fact that single-channel annihilation can serve as a representative for a larger class of models. Some works instead compute the gamma-ray yield for the full set of annihilation channels and branching fraction as predicted from the underlying theory—for example, supersymmetry, pioneered in ref. 2.

Indirect dark matter searches rarely constitute the one and only scientific objective of experiments designed to observe cosmic rays or photons at the upper end of the electromagnetic spectrum. More commonly, putative dark matter signatures are investigated while performing rather conventional cosmic-ray intensity or composition measurements or when surveying the skies in gamma-rays. Indirect dark matter searches are carried out whenever opportunities promise to be sufficiently sensitive in the respective search windows and anticipated parameter space of dark matter candidates. Since dark matter is generally thought to be of universal nature, the universality in conducting indirect dark matter searches connects inevitably with consistency to support the credibility of the findings. Reported anomalies (that is potential or weak indications of a dark matter signature) can be relatively easily strengthened or refuted when further studied in different search regions or using alternative search methods, without the need to build up alternative experiments to do so. The requirements for consistency between different applications of indirect dark matter searches connect seamlessly to aspects of complementarity with other approaches to the detection of dark matter particles, such as direct detection (observation of the scattering of dark matter particles in underground experiments) and/or collider searches for dark matter.

The discovery through indirect detection techniques requires a profound understanding of both the astrophysical backgrounds and the uncertainties imposed by the dark matter model. In addition, predictions for the reach of indirect detection are plagued mainly by the uncertainty in the spatial distribution of dark matter. The expected flux from dark matter annihilations is proportional to the integral of the dark matter density squared over the line of sight and the solid angle subtended by the observation. This integral is traditionally referred to as the ‘\(J\)-factor’. The uncertainties in the density distribution consequently lead to systematic uncertainties.

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¹Oskar Klein Center, Physics Department, Stockholm University, Roslagstullsbacken 21, Stockholm SE-10691, Sweden. ²Institute for Astro- and Particle Physics, Innsbruck University, Technikerstrasse 25/8, Innsbruck 6020, Austria. *e-mail: olaf.reimer@uibk.ac.at
that range between factors of a few to orders of magnitude, dependent on what target is chosen. For decaying dark matter, the respective cross-section enters linearly, with the corresponding integral being sometimes referred to as the ‘D-factor’.

These uncertainties per se do not impact on the credibility of any discovery. However, an additional challenge for indirect detection is the fact that astrophysical sources, especially in the usual regime of limited statistics, can mimic sources of dark matter annihilation. Whereas direct detection also suffers from (comparably smaller) astrophysical uncertainties, mainly in the dark matter velocity distribution and local dark matter density, direct detection appears to be the most straightforward method for discovery, leaving the credibility subject only to the ambiguity in controlling the experimental setups and instrumental backgrounds. Particle collider searches can discover dark matter candidates, and once the connection is made between these candidates and cosmological dark matter, they have the chance to elucidate the properties of dark matter. However, once again, owing to the uncertain nature of the potential interaction channels, collider searches might still fail even if the mass range would suffice. Finally, indirect dark matter search techniques can benefit from serendipity. Discoveries in the high-energy universe have the potential to reveal places with extremely promising characteristics for dark matter studies, and the indication of anomalies, interpreted as potential dark matter signatures, may arise as the by-product of studying other astrophysical phenomena. The history of discoveries in astronomy, cosmology and astroparticle physics testifies that serendipity, while unable to deploy into an active search method, did bring substantial insights.

How to search for dark matter using indirect methods?

There are a variety of anticipated experimental signatures of particle dark matter that leave imprints in the observable energy spectra and/or spatial distribution of gamma-ray photons or charged cosmic rays. Statistical techniques to exploit such signatures—foremost the multi-dimensional profile likelihood and template-fitting signal decomposition—have had significant impact on the progress of indirect detection.

A principal challenge for indirect detection methods is the issue of source confusion and poorly determined backgrounds. It is well known that, both for the gamma ray and the charged cosmic-ray channel, pulsars provide spectral signatures that are in most practical cases indistinguishable from dark matter. So far the only known smoking-gun signal indirect detection can provide is therefore based on the unique spectral features, the most spectacular being a spectral line originating from the annihilation of dark matter particles with each other, resulting in either two photons or a boson and a photon (or both, for multiple lines)\(^1\)\(^2\). Generically, such processes are suppressed, as they are almost exclusively possible via loop processes, but different mechanisms can lead to enhancements\(^3\)\(^4\). Distinctive spectral features not only provide a smoking-gun signal, but they also allow the experimentalist to choose a data-driven method for inferring the background, as control regions are easily defined in this case.

There are celestial regions where dark matter searches appear more promising. As detailed below, this relates to the anticipation of the successful distinction between dark-matter-related emission signatures and the omnipresent astrophysical backgrounds. When exploring over-densities in gravitationally bound matter, the regular morphology of dark-matter-related signals turns out to be a powerful discriminator against usually unevenly structured astrophysical emissions. \(N\)-body simulations of the cosmic structure allow for the prediction of spatial mass density profiles, with the common features among them being smooth and regular density gradients away from a central mass or mass assembly, parametrized as the Navarro–Frenk–White, Einasto, Moore, or Burkert dark-matter-halo density distributions\(^5\)\(^6\)\(^7\).

An indirect method seeking for evidence for dark matter annihilation on cosmological scales\(^8\)\(^9\) measures the cross-correlation between astronomical object catalogues\(^10\)\(^11\) or gravitational distortion in the weak lensing regime\(^12\)\(^13\) and the extragalactic gamma-ray background. Whereas a positive correlation is the principal evidence for the cosmological origin of the extragalactic gamma-ray background, cross-correlation signals originating from dark matter annihilation are anticipated to be different from those of astrophysical foregrounds. The intensity, spectrum, and spatial distribution of resolved and unresolved gamma-ray sources, as well as large-scale galactic emission\(^14\)\(^15\), leave imprints on different angular scales than those of annihilating dark matter particles. The degeneracy between different scenarios and contributions is anticipated to be reduced when the angular cross-correlation is investigated by considering a multitude of astronomical object catalogues, and in different energy windows. Another way to investigate the extragalactic gamma-ray background for dark-matter-induced angular features (anisotropies) on the cosmological scale emerged by considering the auto-correlation angular power spectrum\(^16\)\(^17\)\(^18\). The predicted shape of the angular power spectrum of gamma rays originating from dark matter annihilation deviates from that caused by other astrophysical sources where intensity and density scale linearly. Guaranteed contributions from unresolved sources to the extragalactic gamma-ray background, as well as astrophysical foregrounds leaving imprints in the angular power spectrum, render the interpretation of the results from this method strongly conditional on the assumptions of the analysis methodology.

Experimental techniques in cosmic-ray physics offer sufficiently precise measurements of the charge, charge-sign, momentum and mass to identify individual cosmic-ray particles or nuclei over a large energy range. This energy scale conveniently corresponds to the mass range of WIMPs. Anomalies in cosmic-ray spectra, or more precisely in the measurements of antiparticles such as...
antiprotons or positrons, as well as sensitive limits on heavier antinuclei, are explored for contributions potentially originating from the annihilation and decay of dark matter particles into pairs of Standard Model particles, subsequently decaying or hadronizing into particles that blend with the cosmic rays from astrophysical sources. The major background in these measurements is no longer the misidentification probability to cosmic-ray particles and heavier nuclei or event statistics, but the distance-, time- and energy dependence of cosmic-ray sources and the propagation leaving an imprint on their relative intensities in a complex way. The excess flux against that predicted from standard scenarios for the origin and transport of cosmic rays could either be interpreted as the imprint from one (or more) sources that supply electrons and positrons to the interstellar medium, or from dark matter annihilation in the TeV range. Inadequacies in the modelling of cosmic-ray transport seem to prevent solving this dichotomy for now. Also the antiproton spectrum is studied for deviations from the pure secondary production in cosmic-ray interactions. In the light of the recent Alpha Magnetic Spectrometer (AMS) data, the situation is even more ambiguous, as recent refinements of the primary cosmic-ray spectra and cross-sections for the calculation of secondary particle production already ease the apparent tension with conventional scenarios. Other antinuclei, for example, antideuterium, antihelium and so on, have never been detected. These observations might, however, become very powerful probes for dark matter searches as the ambiguity regarding the astrophysical backgrounds is mostly absent. Still, the experimental limits are orders above even the most optimistic predictions.

Charged cosmic rays at sub-TeV energies are assumed to be isotropized in their arrival direction when they reach the Earth, with the potential exception of electrons and positrons which could be indicating the presence of a nearby source. Anisotropies in the cosmic-ray flux measured on Earth can be investigated for consistency with proposed dark matter scenarios—for example, the observed arrival directions of high-energy electrons and positrons can be compared to those from alternative astrophysical source scenarios. When comparing the cosmic-ray anisotropy signatures or the rising positron fraction with gamma-ray observations, strong constraints on the dark-matter-related interpretations can be obtained. The interpretation of the intriguing TeV-scale hadronic cosmic-ray anisotropy, in terms of annihilating dark matter is considered to be problematic (see ref. 32 for a recent review).

To dissect the cosmic-ray measurements regarding their relation to either conventional or dark matter-induced astrophysical processes we require a better understanding of the cosmic-ray transport in our Galaxy, either by accessing more realistic propagation scenarios, invoking improved models for radiation fields or refined matter distributions in our Galaxy, and more complete as well as more precisely measured cross-sections for kinematic interactions of cosmic rays.

The most frequently applied indirect dark matter search technique relies on a given set of high-level observational data (for example, gamma-ray skymaps) which are then reanalysed by adding dark-matter-specific spatial distribution templates. The Large Area Telescope aboard the Fermi Gamma-ray Space Telescope (Fermi-LAT) is at present the prime instrument delivering input for signal decomposition techniques, thanks to its large field of view, multi-year exposure, and broad dynamic range in the gamma-rays. Likewise, residual emission features from a given gamma-ray analysis might be further studied, for example, by comparison with model-predicted dark matter annihilation or decay signatures. Improvements in the template decomposition techniques are often accomplished through iterative procedures where a suitable statistical estimator is used to quantify the improvements in the results. The most commonly practised approach involves a pixel-wise Poisson likelihood (see also next section).

Apart from the gain in instrumental sensitivity, which is usually accomplished by increasing the exposure or improvements in the event reconstruction—that is, the mapping between the electrical signals in the detector and the physical properties, as well as the classification of the events into certain particle types or interaction categories—the application of dedicated statistical techniques has led to significant improvements in sensitivity. In particular, Fermi-LAT has implemented a multi-dimensional likelihood analysis which paved the way for the optimal target combination and statistically more accurate treatment of nuisance parameters—for example, the dark matter density estimate by means of the profile likelihood. In this frequentist technique, the observables’ dependence on ancillary (nuisance) parameters is modelled and the parameter estimates are obtained by maximizing the likelihood with respect to them. The profile likelihood has been known in the high-energy physics community for at least thirty years, but gained popularity with the advent of the Large Hadron Collider (LHC) in the past decade. Its application to Fermi-LAT observations of dwarf galaxies lead to the first exclusion of thermally produced WIMPs (for masses below 30 GeV) as being the dominant part of dark matter. The multi-dimensional likelihood approach has then also found its way to searches performed by imaging atmospheric Cherenkov telescopes. The recent very competitive constraints obtained by the HESS collaboration exemplify the power of this approach. It is worth mentioning that similar techniques are also applied in direct searches for WIMPs (see ref. 40 for a recent review).
Where to search for dark with indirect methods?

The detectability of dark matter signatures in gamma rays is proportional to the J-factor introduced before. Obvious locations for indirect dark matter searches are therefore regions of extraordinary matter density (for example, centres of gravitationally bound bodies or assemblies such as galaxies or galaxy clusters), peculiar objects or regions with high dark matter content (clumps, sub-halos, dwarf spheroidal galaxies), and the most prominent large-scale diffuse emission phenomena in the gamma-ray sky. For consistency, indirect dark matter searches explore a range of different targets (Fig. 2).

The largest assembly of matter in our Galaxy is naturally the most searched for location for dark matter signatures. However, it is also the most challenging location to investigate, given the variety of astrophysical objects in the inner Galactic Centre region, ranging from a unique object such as our central black hole Sag A*, to a number of supernova remnants, neutron stars and pulsars. Furthermore, all diffuse emission components in the gamma rays (neutral pion decay, inverse Compton scattering, bremsstrahlung) peak in the Galactic Centre. The brightest and central gamma-ray point source in the region is extensively searched for line-like spectral features, and limits have been placed over both GeV and TeV energies\(^{36,41-45}\). It is now believed that regularly extended emission centred at the Galactic Centre holds more promise for indirect dark matter searches. Indeed, the so-called ‘Galactic Centre excess’\(^{46-52}\) is still not conclusively explained, although recently improved astrophysical source models, including the unresolved stellar population render hypothesis for a unique dark matter explanation of the observed GeV Galactic Centre excess signal, are less likely\(^{53,59-58}\). Millisecond pulsars might be able to account for this anomaly. Since they exhibit a broadband emission spectrum, deeper surveys, for example, at radio wavelength, might enlarge this object’s distribution and shed further light on this anomaly. However, there are contrasting views on whether the population of millisecond pulsars is sufficiently large to account for the observed gamma-ray signal\(^{57}\).

Searching the extended celestial regions is probably no longer limited by the low number of associated photons, but by the systematic uncertainties of the deployed analysis procedure or intrinsic to the experimental detection technique of photons itself. The spatially symmetric and extended gamma-ray halo around the centre of our Milky Way is one of the foremost locations for dark matter signatures. Such a structure is a common feature among the different models for spatial mass density profiles predicted by N-body simulations of the cosmic structure. In the Milky Way, establishing the potential existence of an extended halo is challenging for reasons of inferring the astrophysical foregrounds at the various scales. Resolved sources, point-like or extended, large-scale emission phenomena as predicted for the inverse Compton component in the diffuse galactic emission, the existence of large bipolar outflows (or ‘Fermi bubbles’) and populations of still unresolved sources of known or even unknown nature, add to complications in extracting robust measurements of a dark-matter-related Milky Way halo component. The most prominent galactic emission feature, the diffuse galactic emission (for example, refs 58–60), has been repeatedly searched for anomalies (for example, ref. 61). Manifestations of imperfect instrumental responses or deficits in the realism of emission models constructed to predict the spatial- and spectral intensity of the reported diffuse galactic emission became known. Being a demanding analysis on its own due to the manifold simplifying assumptions and limitations of the models to forecast the diffuse galactic emission in the observables (for example, spectrum, longitudinal and latitudinal profiles, tangents and arm/inter arm contrast and so on), the potential signatures of dark matter annihilation in the diffuse galactic emission so far failed to stand tests of universality and consistency over time and/or independent measurements or observation channels.

The residual gamma-ray signal obtained after accounting for all resolved sources and sufficiently motivated galactic foreground emission phenomena is called the extragalactic gamma-
ray background. It is explained by the cumulative contributions of unresolved sources in source classes that should be able to emit gamma rays at the large galactic scale heights, such as halo-populations like millisecond pulsars, blazar-class active galactic nuclei, misaligned active galactic nuclei, star-forming galaxies, or galaxy clusters. These constituents are considered as guaranteed contributions to the observed extragalactic gamma-ray background signal, albeit being predicted with different level of uncertainty per class and varying prominence over energy compared to each other. Uncertainties in the predictions of the guaranteed astrophysical contributions to the extragalactic gamma-ray background, as well as the potential existence of anisotropies, offer chances to explore the extragalactic gamma-ray background for dark matter annihilation or decay signatures. The respective probes (energy spectrum, cross- and/or auto-correlation angular power spectrum) have been already introduced. Expectations to reveal unambiguous signatures of dark matter in the extragalactic gamma-ray background signal relies in a subtle way on both the extremely elaborate analysis procedure to robustly measure the extragalactic gamma-ray background itself and a precise understanding of the contributions from unresolved source populations. To a certain degree, the measurement of the extragalactic gamma-ray background can then be used to constrain the intensity of potentially dark-matter-related emission and allow placing upper limits on characteristic quantities such as the annihilation cross-section. However, these constraints not only depend on the distribution of dark matter in halos, but also on the abundance of halos and sub-halos and their redshift dependence. Nevertheless, present limits, approaching the most stringent existing constraints, already allow for important consistency checks with those obtained using a different analysis methodology (see ref. 76 for a recent review).

Where are we now?

Indirect detection has provided a number of intriguing indications of a dark matter signal, which usually subsequently disappeared—mostly due to the aforementioned systematic uncertainties, difficult backgrounds and possible source confusion. At present, there are only three anomalies that can be ascribed to dark matter: the rising fraction of positrons as compared to electrons measured by PAMELA and confirmed by AMS, and a hardening of the antiproton fraction reported by AMS, and the excess emission of the Galactic bulge in the GeV gamma rays measured by Fermi-LAT. There is ample literature discussing the influence of systematic uncertainties and possible conventional astrophysical sources explaining these anomalies. Here, it suffices to say that none of these anomalies lack a plausible conventional explanation, and these indications are ambiguous at best. Turning to limits, the currently strongest constraints on the annihilation cross-section and WIMP mass (Fig. 3) come from the analysis of dwarf galaxies. This analysis excludes annihilation cross-sections larger than the thermal cross-section benchmark for dark matter candidates lighter than 100 GeV. Complementary limits (for example, refs 81,82) obtained from recent antiproton measurements substantiate these tight bounds. Likewise, the observations of the central Galactic bulge provide constraints on level pegging. At higher energies, HESS observations of the inner Galactic halo impose the best limits at present.

Where are we heading?

A comparative discussion of the existing experimental approaches can hardly be done without relying on some theoretical preference. If we concentrate on the WIMP, the masses range from a few GeV to 100 TeV. If we further restrict ourselves to supersymmetric WIMPs, multi-TeV WIMPs are generically disfavoured, but on the other hand WIMPs up to 100 GeV are already significantly constrained by the gamma-ray data. Future data obtained by the Fermi-LAT, direct detection experiments, and the LHC will effectively probe the sub-TeV range for WIMP dark matter. The appearance of an unequivocal line signature that will directly reveal the mass of the elusive dark matter particle pronounces line searches as the least ambiguous among all indirect methods. Meanwhile, however, line scans increasingly face the inconvenience that data sets are already scanned increasingly face the inconvenience that data sets are already scannocene the most stringent existing constraints, already allow for important consistency checks with those obtained using a different analysis methodology (see ref. 76 for a recent review).

Figure 3 | The current most important constraints on the annihilation cross-section versus WIMP mass. The constraints are for the annihilation to b-quark pairs. Whereas indirect methods exploring gamma-ray photons and cosmic rays from satellite measurements compete well up to hundreds of GeVs, at higher energies, air Cherenkov telescopes appear to be driving the present limits. The thermal relic cross-section is indicated by the light grey band. Note that different assumptions for the dark matter distributions affect these limits quantitatively, but do not change the situation qualitatively. Data taken from refs 39,80,81,99-104.

Figure 4 | The present and future search capabilities on spin-independent WIMP-nucleon scattering (adapted from ref. 91). The expectation from direct detections (XENON1T/XENONnT/LZ) overlaid on regions preferred by supersymmetric models. The blue colour indicates a regime where the LHC will drive more sensitive constraints; the green region represents a regime where collider-based searches are complemented by indirect searches by the Cherenkov Telescope Array; and the red region depicts a regime most sensitively probed by the Cherenkov Telescope Array. The lower bound on search capabilities imposed by resonant neutrino scattering (light grey) will become the fundamental obstacle for exploring the GeV mass scale window with direct detection. Whereas consistent supersymmetry models providing WIMPs exist at multi-TeV masses and below the neutrino background, they may not constitute the most favoured parameter regions. Data in taken from refs 105,106.
are not expected to substantially improve beyond the present sensitivity limits. Only if a significantly better energy resolution in the high-energy gamma-ray experiments becomes an experimental reality, might things change. Indeed, there are a number of satellite projects that will provide energy resolutions close to one percent. However, outside the WIMP paradigm, at similar interaction strength, but predicting somewhat lower masses, is asymmetric dark matter. Line searches will also see further application as soon as different energy scales, either towards lower (MeV) or towards higher energies (PeV), become accessible. Until then, the most promising investigations are consequently those where the number of objects studied can be substantially enlarged and translated into more stringent bounds. Likewise, discoveries of more strongly dark-matter-dominated objects, perhaps also located in regions without substantial contributions from the astrophysical backgrounds, presently constitute the most promising way to drive indirect searches beyond the existing constraints. Gaining from the deep cosmological surveys (most notably by the Panoramic Survey Telescope and Rapid Response System, Dark Energy Survey, Large Synoptic Survey Telescope), dark matter sub-halos/dwarf spheroidal galaxies appear to be the class of objects that holds the best promise to go beyond even the most stringent current limits. For controlling the systematics, the most promising venue to constrain the extragalactic J-factors is probably related to gravitational lensing investigations. As for the Galactic J-factors, current and upcoming Galactic stellar surveys such as GAIA might help to improve the situation.

The privilege to accommodate all indirect search techniques using GeV-scale gamma rays has over the past decade elevated the Fermi-LAT as the most widely used instrument for indirect searches. The steady accumulation of exposure and gradual improvement of the instrumental response functions, as well as the application of elaborate analysis techniques, underline the impact of studies utilizing the Fermi-LAT data. At higher energies, the present generation of atmospheric Cherenkov telescopes—most notably HESS, MAGIC and VERITAS—have contributed decisively to dark matter searches. Follow-up instruments with largely improved sensitivity and/or dynamic range will go beyond these accomplishments. The extended energy range of the High-Altitude Water Cherenkov Observatory (HAWC), the Large High Altitude Air Shower Observatory (LHAASO) and, in particular, the Cherenkov Telescope Array (CTA) will allow for searches in a regime presently underexplored or not accessible at all. This appears to be the unique upcoming discovery window for indirect dark matter searches, relating to dark matter candidates on the rather heavy side of the mass scale. These facilities will be able to exceed the present upper bounds of indirect searches using gamma-ray photons. Search opportunities at lower energies are obviously hampered by the void of space instruments since the Compton Gamma-ray Observatory from the era of NASA’s large telescopes. Proposed new low-threshold gamma-ray telescopes such as EASTROGAM or COMPARE might provide prospects for dark matter detection in this underexplored energy regime.

The cosmic-ray channel has been most effectively used over the past decade by the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) satellite. The Alpha Magnetic Spectrometer (AMS) has by now taken over the frontier of dark matter searches in cosmic rays and will dominate studies in the cosmic-ray channel for a substantial period of time. Instruments such as the DAMP Dark Matter Particle Explorer (DAMPE), the CALorimetric Electron Telescope (CALET), and the High Energy cosmic-Radiation Detection (HERD) hold promise to advance beyond the state of the art in their investigations of signatures in the electron and gamma-ray energy spectra.

We have discussed the potential for indirect detection techniques. If dark matter particle candidates are discovered by the LHC, astrophysical detection will be necessary to connect the produced particle(s) with the cosmic dark matter. Direct probes dark matter on galactic scales. Indirect detection (including probes in other wavelengths such as optical, radio and microwaves), on the other hand, is the only technique that can probe the particle nature of dark matter on cosmic scales and will continue to do so.

Any attempt to compare the reach of different approaches remains necessarily model-dependent. When the supersymmetric WIMP is considered, the result is usually largely dependent on the implementation of the supersymmetry-breaking mechanisms and other choices. Attempts to facilitate the comparison in a more general framework, either using an effective field theory or the so-called simplified models, that reduce the dark matter model to be described by two couplings, a mediator mass and the dark matter mass, are underway, but largely lacking for indirect detection. With this caveat in mind we illustrate in Fig. 4 the reach of indirect detection (focusing on the CTA) as compared to future direct searches, and the parameter space that will be covered by collider-based searches at the LHC (Run 1 at 8 TeV and predictions for Run 2 at 14 TeV in 2023), within the rather generic framework of the 19-dimensional phenomenological Minimal Supersymmetric Model (pMSSM) for example, ref. 91. It becomes evident that, firstly, there is an ultimate limit that will decisively hamper direct search methods: the background expected from coherent neutrino scattering. Many potential realizations of the pMSSM fall below this boundary, even if admittedly most of these do not really easily qualify for being called ‘miracle WIMP’, as they will not generically dominate the dark matter and arguably are not favoured by current data. Secondly, for WIMP masses above about a TeV, only direct detection and indirect detection have significant discovery potential, and thirdly, among these high mass WIMP models there are those that are within reach only for the CTA. Considering time lines for current and future experiments, as well as robustness of predictions, it appears that the unique capabilities for indirect detections are to be found at WIMP masses above a few TeV—that is, masses that are not generically preferred by the naturalness requirements on supersymmetry, but certainly allowed by the WIMP paradigm. From another perspective, however, at masses between about 100 and a thousand GeV there seems to be a non-negligible chance for detection by different search techniques, which would not only provide the necessary confirmation of LHC discoveries but also help to constrain the properties of the dark matter particle. It remains to be seen if indirect search methods will continue to play their role like they have over the past decade.

Given the increasing pressure on the thermally produced WIMP dark matter, especially considering future direct and indirect detection, other particle candidates will have to be considered on equal footing as potential WIMP candidates. Among the foremost of these is probably the QCD axion to solve a fine-tuning problem related to charge parity (CP) violation in the quantum chromodynamics (QCD) sector. Despite the prediction of QCD axions coupling to gamma rays, the QCD axion, which has a predicted relationship between coupling and mass, is probably not within the reach of indirect detection experiments. Relaxing the model space to axion-like particles (which are a feature of many models beyond the Standard Model), gamma-ray observations are providing constraints which are competitive with the present and planned laboratory experiments.

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Competing financial interests

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