Indirect Detection of Dark Matter with γ rays

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The details of what constitutes the majority of the mass that makes up dark matter in the Universe remains one of the prime puzzles of cosmology and particle physics today - eighty years after the first observational indications. Today, it is widely accepted that dark matter exists and that it is very likely composed of elementary particles – that are weakly interacting and massive (WIMPs for Weakly Interacting Massive Particles). As important as dark matter is in our understanding of cosmology, the detection of these particles has so far been elusive. Their primary properties such as mass and interaction cross sections are still unknown. Indirect detection searches for the products of WIMP annihilation or decay. This isq generally done through observations of gamma-ray photons or cosmic rays. Instruments such as the Fermi-LAT, H.E.S.S., MAGIC and VERITAS, combined with the future Cherenkov Telescope Array (CTA) will provide important complementarity to other search techniques. Given the expected sensitivities of all search techniques, we are at a stage where the WIMP scenario is facing stringent tests and it can be expected that WIMPs will be either be detected or the scenario will be so severely constrained that it will have to be re-thought. In this sense we are on the *"Threshold of Discovery"*. In this article, I will give a general overview over the current status and the future expectations for indirect searches for dark matter (WIMP) particles.

Gamma rays | Dark Matter | Cosmology

There is a broad consensus that dark matter is made up of elementary particles. The most promising candidates are weakly interacting massive particles (WIMPs), particularly if they also form the lightest supersymmetric particle. The general assumption is that the thermal freeze-out in the early Universe leaves a relic density of dark matter particles in the current Universe (after the freeze-out the particles become too diluted to annihilate in appreciable numbers and thermal energies were too low to produce them. The co-moving density is therefore roughly constant since then). The annihilation of these particles into standard-model particles controls the abundance in the Universe, there is thus a tight connection between the annihilation cross section and cosmologically relevant quantities. For particles annihilating (in the simplest case, i.e. annihilating through S waves [1]) the relic density only depends on the annihilation cross section σ_{ann} weighted by the average velocity of the particle (see e.g.[2]):

$$\Omega_\chi h^2 = 0.11\,\frac{3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{<\sigma_{\mathrm{ann}} v>}$$

As the value for the relic dark matter density from CMB observations is $\Omega_\chi h^2 = 0.113 \pm 0.004$ [3], it follows that the expected velocity-weighted annihilation cross-section is in the range of $3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$. This represents a striking connection that for typical gauge couplings to ordinary standard model particles and a dark matter mass at the weak interaction scale WIMPs have the right relic density (using standard early Universe conditions) to match those of the cosmologically measured dark matter particles. In other words, the value for $<\sigma_{\mathrm{Ann}} v>$ corresponds to a cross section of approximately 1 pb, i.e. a typical weak interaction cross section. This is the so-called WIMP miracle in which particles that are motivated by a microphysical puzzle (or better a gauge hierarchy problem) are excellent dark matter candidates. Obviously, this connection could be merely a coincidence but if true, then naturally, WIMP masses would be expected in the range of 10 GeV and a few TeV which is why a lot of attention has been devoted to exploring that mass range in the dark matter parameter space.

Given the tight connection between the amount of WIMP dark matter in the current Universe and the annihilation cross-section it is natural to expect dark matter self-annihilations. To be able to self-annihilate the dark matter particle much either be a Majorana particle or a Dirac particle with no matter-antimatter asymmetry. In the annihilation (or decay) of the dark matter particles all kinds of standard model particles are created (quarks, bosons, leptons) and then produce either gamma rays or cosmic rays. In particular regions in the Universe with high dark matter densities (such as the centers of galaxies, and clusters of galaxies) have enhanced probabilities that dark matter particles encounter each other and annihilate. With an appropriate assumption about the density distribution of dark matter (e.g. from numerical simulations) one can predict the expected annihilation signal when assuming a certain annihilation cross section or put limits on the latter in the absence of a signal.

A more quantitative description of the expected flux of particles from dark matter annihilation can be drawn from the following relation:

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{dE}_\gamma} = \underbrace{\frac{1}{4\pi}\,\frac{<\sigma_{\mathrm{ann}} v>}{2\mathrm{m}^2_{\mathrm{WIMP}}}\sum_f \frac{\mathrm{dN}^f_\gamma}{\mathrm{dE}_\gamma}\mathrm{B}_f}_{\text{'Particle Physics'}} \times \underbrace{\int_{\Delta\Omega} \mathrm{d}\Omega' \int_{\mathrm{los}} \rho^2 r(l,\theta')\mathrm{d}l(r,\theta')}_{\text{'Astrophysics' or } J(E)}$$

The left-hand side contains the (measureable) gamma ray flux. The right-hand side contains two components (1) a particle physics term which is given by the velocity-averaged annihilation cross-section ($<\sigma_{\mathrm{ann}} v>$), the mass of the dark matter particle (m) and the sum over the gamma-ray yields for a certain annihilation channel into channel f ($\mathrm{dN}^f_\gamma/\mathrm{dE}_\gamma$) multiplied by the branching ratio into that channel (B_f), and (2) an astrophysics term $J(E)$ (called the J-factor) given by the line-of-sight integral of the square of the dark matter density ρ. Given that both the particle physics and the astrophysics term are unknown, one needs to make an assumption about one in order to put constraints on the other when measuring a gamma-ray flux (or an upper limit). This in turn already points to one of the major challenges in the indirect detection of dark matter: the astrophysical uncertainties, both in the density profile of dark matter (which enters quadratically) and in the suppression of the astrophysical foregrounds (which affect the sensitivity or the minimal gamma-ray flux that can be

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detected). In order to derive meaningful dark matter limits, the astrophysical foregrounds have to be understood and subtracted. For excellent general recent reviews on selected topics related to the indirect detection of dark matter, see [4, 5, 6, 7].

While most recent studies to detect the secondary products of dark matter annihilations have focussed on gamma rays, annihilations into cosmic rays can also be used. Given the large flux of cosmic rays accelerated directly in astrophysical sources (primary cosmic rays) and produced in the interaction of cosmic rays with interstellar material (secondary cosmic rays) it is beneficial to use particles that are less-frequently produced in these settings. The most commonly used are antimatter particles, in particular anti-deuterons, anti-protons and positrons, which are not so copiously produced in astrophysics accelerators. These can provide important clues towards the dark matter puzzle as e.g. seen in the rise in the positron fraction recently observed by PAMELA [8] and confirmed by the Fermi-LAT and AMS [9, 10]. However, I will mention them in this article only in passing and will focus on gamma-ray observations.

Gamma rays can be produced by dark matter annihilations in two major ways: (a) continuum signals from annihilation into other particles which eventually produces gamma rays either through pion production, or final state bremsstrahlung and inverse Compton from leptonic channels and (b) line signals from dark matter annihilating directly to γX, where X usually is another neutral state, typically γ ray or Z or a Higgs boson. Given that dark matter particles are essentially at rest (for cold dark matter), the photons will emerge back-to-back with an energy directly related to the rest mass of the dark matter particle $E_\gamma = m_\chi$ or $E_\gamma = m_\chi(1 - m_X/4M_\chi^2)$. While the line signal can provide a "smoking gun" signal for dark matter annihilation, its flux is typically loop suppressed by a factor of α_e^2 where α_e is the fine structure constant (the electrically neutral dark matter particle does not couple directly to photons but has to go through a charged particle loop) . The signal is therefore expected to be much smaller than the continuum flux. This continuum signal has a smooth energy distribution with an exponential cutoff at the mass of the dark matter particle $E_\gamma = m_\chi$. The spectral shape is universal in the sense that it takes a similar form for almost any channel and depends somewhat weakly on m_χ. The exact annihilation channel depends on the properties of the WIMP but is typically (for bino-like WIMPs) dominated by annihilation into $b\bar{b}$ pairs with pair production into τ-leptons also contributing. For more massive WIMPs with a wino or higgsino component annihilation will proceed into massive gauge bosons. Annihilations that have a large branching fraction into e^+e^- pairs will enhance the gamma-ray signal through inverse Compton scattering these on starlight or the CMB (see e.g. [11, 12]).

Gamma rays have several unique properties which make them ideally suited to study dark matter annihilations. Primarily, they do not get deflected in intervening magnetic fields and thus point back at the site at which they are created. This allows one to search for gamma ray signatures not only in our vicinity in the Galaxy but also in distant objects such as satellite galaxies or even galaxy clusters. In the case of a signal, this could make provide a unique method to study the distribution of dark matter in our Galaxy or in the Universe. The energy of gamma rays from dark matter annihilation is limited by the rest mass of the annihilating particle. Gamma rays therefore also provide a unique spectral signature. In particular, given the aforementioned preferred WIMP masses at the scale of a weakly interacting particle, gamma-rays in the GeV and TeV range access the most relevant mass range of dark matter particles. One final advantage of the usage of gamma rays is that, in the local Universe gamma-rays do not suffer from attenuation, and therefore they retain the source spectral information intact at the Earth.

In the following section I will summarize current observational results with a focus on gamma-ray observations. Currently, the most productive observatory for dark-matter related publications is the Fermi-LAT with currently ~200 such refereed publications. The Fermi-LAT has recently provided a major breakthrough in the indirect detection of dark matter by reaching for the first time below the aforementioned thermal relic annihilation cross-section of $3 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ through observations of dwarfs spheroidals. The final section will give an outlook for future prospects in indirect dark matter observations and will also discuss the complementarity of the various search methods.

Observational results

Targets for dark matter searches. Because of the quadratic dependence of the self-annihilation rate of dark matter and thus the gamma-ray flux the detectability of any particular region in the Universe strongly depends on the density distribution along the line of sight of the dark matter particles (so-called J-factor). Unfortunately, dark matter densities are not very well constrained by numerical simulations, especially in the innermost regions. In fact, simulations originally showed that the collapse of cold dark matter gives rise to rather cuspy dark matter haloes (something that would favor the indirect detection of dark matter because of the ρ_{DM}^2 dependency). On the other hand, observations of galaxy rotation curves favor constant density cores (so-called 'cusp-core problem", see e.g. [13, 14, 22, 23]). An additional complication stems from substructure in the dark matter distribution that is currently not resolved in cold dark matter N-body simulations, (i.e. below $\sim 10^5 M_\odot$). This unresolved substructure can have a very large impact, in particular in objects such as galaxy clusters. Since substructure will further enhance the annihilation signal this effect is typically quantified in terms of the so-called boost factor B defined as the ratio of the true line-of-sight integral to the one obtained when assuming a smooth component without substructure. Finally, the situation is further complicated by the fact that for many objects (such as e.g. the Milky Way) baryonic matter dominates the inner parts of the gravitational potential. Baryons are expected to have a significant impact on the dark matter profile compared to the numerical simulations which are generally dark matter-only. The infall of baryons is expected to alter the inner dark matter profiles. The profile could either be steepened through adiabatic contraction [15, 16, 17], or it could be flattened through the occurrence of repeated star bursts triggered by baryonic infall which tends to render the gravitational potential shallower since the star burst activity drives out the baryons from the inner parts [18, 19, 20].

The choice of the assumed profile of the density distribution constitutes therefore one of the prime uncertainty in studying dark matter using gamma rays. As will be discussed later, the uncertainty on the resulting expected flux limits for individual dwarf spheroidals are between a factor of 3 for well-constrained objects like Sculptor up to a factor of 10 for objects such as Coma Berenices. For the Galactic center, arguably the most promising target in terms of expected gamma-ray flux from dark matter annihilations, these uncertainties are considerably larger. See [21] for a discussion on the dark matter profile in the inner Galaxy from a meta-analysis of kinematic data of the Milky way. Estimates can differ by

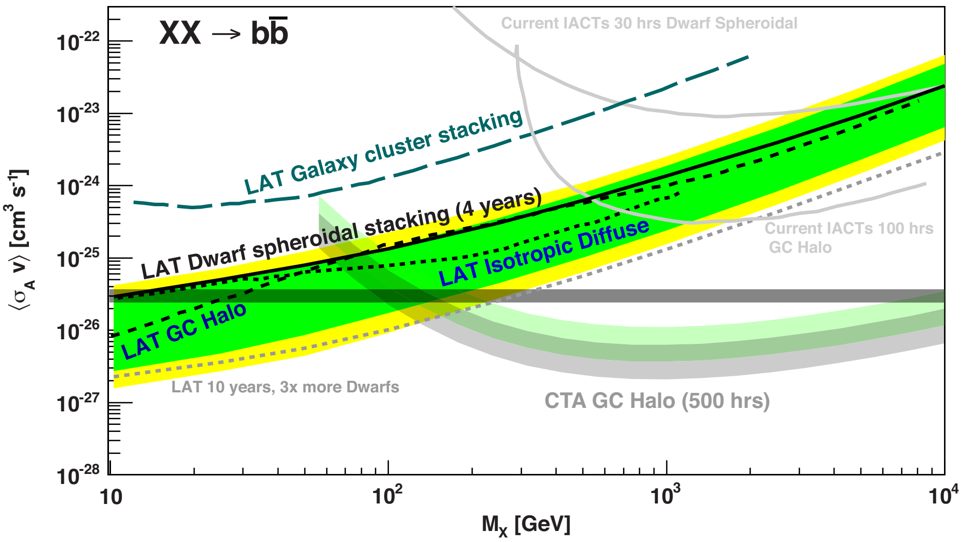

Fig. 1. Compilation of current limits from the Fermi-LAT on dark matter annihilation cross-section σ using gamma rays, along with projected future limits from the Cherenkov Telescope array (CTA). The Fermi-LAT limits were taken from the Fermi-LAT paper on dwarf spheroidals [24] (solid black), on the isotropic diffuse [56] (dotted), on the galactic center halo for an NFW profile [62] (dashed), and on the stacking of galaxy clusters [37] (long dashed). The yellow (95%) and green (68%) bands give the range of expected limits when repeating the procedure multiple times in Monte-Carlo simulations on dwarf spheroidals without the inclusion of a signal. The light green (Einasto) and light gray (NFW) band give the expected CTA sensitivity (500 hours) for the Galactic center halo under the assumption of two different dark matter profiles. For these CTA estimates, the contribution by the US groups (doubling the number of mid-sized telescopes) was taking into account [96]. For the Einasto halo model the shape parameter was fixed to 0.17. For both models the density was normalized to 0.4 GeV cm^{-3} at the solar radius. For the sensitivity curves, the signal was evaluated by integrating the product of the gamma-ray acceptance and the differential DM flux over an annulus of 0.3 - 1.0 deg from the GC. The background in the signal region was calculated from the product of the signal region solid angle and an energy-dependent model for the spatial density of protons and electrons that survive background rejection cuts. In addition, the uncertainty on the background was modeled by assuming the existence of a control region with a solid angle five times that of the signal region.

up to a factor of 50 depending on the choice of the profile. For clusters of galaxies the main uncertainties come from the treatment of substructure below the resolution limit of current numerical simulations. Also here, the uncertainties in the J-factor can be several orders of magnitude, and the dark matter profile itself can be severely modified in these objects by the presence of substructures. In the following I will go through indirect detection observations of the various targets, highlighting current upper limits to WIMP annihilation/mass cross-sections.

Dwarf Spheroidals. In contrast to the aforementioned uncertainties in the inner parts of the density profile of objects on Galaxy or galaxy cluster scales, dwarf spheroidal galaxies can represent a very clean system to search for dark matter annihilation. Indeed, star formation is usually very much suppressed in these objects, so astrophysical foregrounds that produce gamma rays are less of an issue in these objects. From the stellar kinematics the DM content can appropriately be determined, and these objects have been found to be the ones with the largest mass-to-light ratios in the Universe. Boost factors through substructure below the resolution of numerical simulations are expected to be irrelevant in these objects and therefore do not add a large uncertainty. Uncertainties related to the shape of the dark matter profile are generally integrated over and therefore introduced by the choice of the profile are at the 10-50% level. Currently, there are roughly 25 known dwarf satellite galaxies to the Milky Way and both ground-based instruments such as H.E.S.S., MAGIC and VERITAS as well as the Fermi-LAT are actively observing these objects. While none of the objects are detected with the current generation of gamma-ray instruments, important conclusions on the properties of dark matter particles can be drawn from these objects. In particular, a combined analysis of all known dwarf satellites with the Fermi-LAT have pushed, for the first time the annihilation cross section limits below the canonical thermal relic production cross-section of $3 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ for a range of WIMP masses (around 10 GeV) for the annihilation into $b\bar{b}$, which often acts as a benchmark [24, 25, 26]. This statement holds also if uncertainties in the J-factors for these objects are included. Given the all-sky capability of the Fermi-LAT, a combined analysis of these objects will remain the cleanest target in the future where more dwarfs are expected to be detected with future optical surveys such as Pan-STARRS [27], DES [28] and LSST [29]. It has been estimated that DES might discovery 19 to 37 new dwarf galaxies during the duration of the Fermi-LAT mission [30]. At higher energies ground-based Imaging Atmospheric Cherenkov telescopes (IACTs) have observed dwarf spheroidals but have not found a signal [31, 33, 32]. Their limits for high WIMP masses are typically several orders of magnitudes away from the thermal relic cross section and are therefore not (yet) competitive with limits from the Fermi-LAT at lower energies.

Galaxy Clusters. Galaxy clusters are the largest massive objects in the Universe. Galaxy clusters are more distant than dwarf spheroidal galaxies or any of the other targets that are generally used for dark matter studies using gamma rays. However, like dwarf spheroidals, they are likely to be dark matter dominated. The range of proposed boost factors due to unresolved dark matter substructure can be large. Depending on the assumption about the substructure Galaxy clusters become competitive in their expected annihilation signal with dwarf spheroidals only at the extreme (high) end of boost factors. The best candidate are massive nearby clusters such as Virgo, Fornax or Coma [34, 35, 36]. One complication for a possible detection is that galaxy clusters are also expected to contain a significant number of astrophysical sources of gamma rays, such as Active Galactic Nuclei (AGN) or radio galaxies. In addition, these objects are expected to harbor a significant population of cosmic rays which should radiate gamma rays through interaction with hadronic material and subsequent pion-decay. As long as no signal is found, ignoring this contribution represents a conservative assumption and is therefore justified [37, 38, 39, 40, 35]. Early claims of a signal in the Fermi-LAT data from the Virgo cluster [41] turned out to be due to a several unmodeled point-sources within the cluster [42]. At higher energies ground-based instruments have pushed for rather stringent gamma-ray flux limits on galaxy clusters (e.g. the MAGIC telescopes for the Perseus cluster [43], the VERITAS array for the Coma cluster [44], and the H.E.S.S. array for the Fornax cluster [45]). However, when making conservative assumptions about boost factors in these objects, the limits on the benchmark b$\bar{\text{b}}$ annihilation channel are several orders of magnitude away from the canonical thermal relic cross section.

Isotropic diffuse emission. The Fermi-LAT has provided a measurement of a faint diffuse isotropic signal from all over the sky. This so-called isotropic gamma-ray background (IGRB) follows a featureless powerlaw from 200 MeV to 100 GeV [46] with a photon index of 2.4. This signal is expected to contain a contribution of mainly extragalactic unresolved (subthreshold) sources combined with potentially truly diffuse emission. An analysis of the populations of the most numerous sources detected by Fermi during the first years – blazars – showed that unresolved such objects contribute at most 30% of the IGRB emission [47, 48]. It is thus possible that the IGRB emission contains the signature of some of the most powerful and interesting phenomena in astroparticle physics. Intergalactic shocks produced by the assembly of Large Scale Structures [49, 50, 51], gamma-ray emission from galaxy clusters [52, 53], emission from starburst and normal galaxies [54, 55], are among the most likely candidates for the generation of diffuse GeV emission. In addition, and most relevant for this review, a signal from dark matter annihilation could be imprinted in the IGRB. While it would be extremely difficult to detect a dark matter contribution in the IGRB, upper bounds on dark matter annihilation can be readily derived. The most conservative approach when calculating upper limits on the dark matter annihilation cross section is to assume that all of the IGRB is caused by dark matter annihilation. When making rather conservative assumptions about the contribution of source populations to the IGRB dark matter annihilation cross section limits can be derived [56, 57, 58, 59] that are competitive with other methods, such as dwarf spheroidal galaxies. Obviously, these limits can be significantly tightened when including additional source populations - however, the degree to which the contribution from such classes can be determined is questionable. However, even for the more conservative limits, when combined with H.E.S.S. observational constraints from the Galactic center halo, the IGRB fluxes rule out all interpretations of the PAMELA positron excess based on dark matter annihilations into two final lepton states [57] and most of the parameter space for annihilation into four leptons through new intermediate states.

The statistical properties of the IGRB additionally encodes information about the origin of this emission. Unresolved sources are expected to induce a different level of small-scale anisotropies compared to truly diffuse contributions. A study of the angular power spectrum of the diffuse emission at Galactic latitudes $|b| > 30^\circ$ between 1 and 50 GeV revealed angular power above the photon noise level at multipoles $l > 155$ independent of energy [60]. The scale independence of the signal suggests that the IGRB originates from one or more unclustered populations of point sources. The absence of a strong energy dependence suggests that a single source class that provides a constant fractional contribution to the intensity of the IGRB over the energy range considered may provide the dominant contribution to the anisotropy. Recently it has been suggested that a strong correlation between cosmic shear (as measured by galaxy surveys like DES and Euclid) and the anisotropies in the IGRB might add an additional handle on the contribution of dark matter annihilation to the IGRB [61].

Because of their limited field of view and the irreducible electron-shower background, ground based instruments so far have not provided a competitive measurement of the IGRB. However, the Fermi-LAT is expected to eventually measure the signal up to several TeV.

Galactic Center. The Galactic center is expected to be the brightest source of dark matter annihilation gamma rays by at least two orders of magnitude. However, a multitude of astrophysical sources of gamma rays in that region complicate the identification of any source region with dark matter annihilations. For GeV gamma rays the situation is further complicated by the presence of a highly structured and extremely bright diffuse gamma-ray background arising from the interaction of the pool of cosmic rays with dense molecular material in the inner Galaxy. These astrophysical foregrounds are expected to be several orders of magnitude brighter in gamma rays than the signal from dark matter annihilations. Because of these, searches for dark matter annihilation are usually performed in regions excluding the very center of the Galaxy. In addition, because of the proximity the gamma-ray distribution can be expected to be resolved and therefore the exact choice of the expected radial profile of the dark matter distribution has a rather large effect when deriving the limits (in choosing the optimal extraction region). Data from the Fermi LAT have been used to search for an annihilation signal from the galactic dark matter halo [62] and also from the central part of the Galaxy [63]. In both cases rather conservative limits that assume only the Galactic diffuse emission and dark matter annihilation to contribute to the observed signals provide limits that are comparable to those reached by the stacking of dwarf spheroidals. Of course, these limits can be pushed further down with increasing assumptions about the objects producing the observed gamma-ray emission in the galactic center [64]. However, increasing the complexity of the "foreground modeling" will also make these limits less robust.

At TeV energies, the H.E.S.S. telescope system has detected a point-source coinciding with the supermassive black hole in the center of our Galaxy [65] and a diffuse emission coinciding with molecular material in the Galactic ridge [66]. The galactic center source has a featureless powerlaw spectrum at TeV energies with an exponential cutoff at ~ 10 TeV which does not lend itself easily to a dark matter scenario and is therefore generally thought to be either related to the supermassive black hole Sgr A* [67] or a pulsar wind nebula in that region [68]. Because of the presence of these bright sources the search for a dark matter signal has focussed on an angular region of $0.3^\circ - 1.0^\circ$ around the galactic center. Using 112 hours of observation time, the H.E.S.S. collaboration has set the most constraining limits on the annihilation cross section for masses > 1 TeV, reaching $\sim 7 \times 10^{25}\mathrm{cm}^2\mathrm{s}^1$ at 1 TeV for the b$\bar{\text{b}}$ channel [69].

Even more interesting, there have been two hints of a signal in the galactic center region. First, there were reports of an extended signal coinciding with the center of our Galaxy [70, 71, 72, 73] above the galactic diffuse emission. There are various alternatives for the origin of this signal, amongst others the interaction of freshly-produced cosmic rays with interstellar material [70, 72, 74, 75], a population of mili-second pulsars [76, 77, 78], or the annihilation of dark matter particles with masses between 7 and 40 MeV [70, 71, 72]. While the signal appears to be real and naturally is of great interest, the lack of a smoking gun feature that could help relate it to dark matter annihilation will make it extremely difficult to convincingly and unambiguously claim a dark matter detection unless backed by other measurements.

In that regard, the second claimed signal in the galactic center region is even more exciting, the discovery of a line signal at ~ 130 GeV in an extended region around the galactic center. I will describe its general properties in the following section.

Line Searches. The annihilation of dark matter into γX leads to monochromatic gamma rays with $E_\gamma = m_\chi(1 - m_X/4M_\chi^2)$. Such a signal will provide a smoking-gun signal that is very difficult to mimic in astrophysical sources, in particular if found in more than one location on the sky. This process is expected to be strongly loop-suppressed by a factor $\mathcal{O}(\alpha_{\rm e}^2)$. The discovery of a hint of a signal at ~ 130 GeV in the Fermi-LAT data in a region-of-interest (ROI) optimized for particular dark matter distributions towards the Galactic center [79, 80] have raised the exciting possibility that if confirmed this could be the long awaited first clear evidence of dark matter annihilation into gamma rays. While very serious doubts about the astrophysical origin of the signal have been raised recently as will be discussed below, the statistical significance of the original signal seems to be beyond the level of a statistical fluctuation. Two obvious alternatives to a dark matter annihilation signal exist: (1) an astrophysical origin (such as e.g. inverse Compton scattering in the Klein-Nishina regime of mono-energetic electrons produced in pulsar winds [81]) and (2) one or more systematic (i.e. instrumental) effects. Given that the signal was found to be significantly extended, the pulsar hypothesis can safely be discarded and therefore the only viable alternative explanation is an instrumental effect.

Although only marginally significant (claimed post-trial significance of 3.2σ), the community has enthusiastically responded to this signal. The extension of the signal seems to be compatible with conventional dark matter profiles such as NFW or Einasto and slightly offset but generally in the direction of the Galactic center [82, 83]. There was a mild tension with all-sky limits for dark matter annihilation lines released around the same time by the Fermi-LAT team [85] but that could be argued was due to the difference in extraction region (all-sky versus optimized ROI for a particular dark matter profile). Additional studies quickly suggested a second line at 114 GeV that – in the picture of dark matter annihilation – was identified as the $\chi\chi \leftarrow \gamma Z^0$ line [82] (although only at the $1-2\sigma$ level). Line signals at 130 GeV at low significance were also claimed to be detected from unidentified sources [86] and from galaxy clusters [87].

Compared to these early indications, the picture has, however, become significantly murkier at closer inspection – instrumental effects do seem at least to play a role in this signal. Early doubts that the signal could be a contamination of the background estimate arising from the spectral shape of the Fermi bubbles (power law with sharp break) in that region [88] were likely ruled out based on the morphology of the signal [89]. The spectrum of most of the unidentified sources that showed the weak hint of two lines at similar energies to the original galactic center signal were shown to be incompatible with a dark matter annihilation origin [71, 90] but rather in agreement with those from active galactic nuclei (AGN). This finding therefore challenges the notion of the signal arising from DM annihilations and makes an instrumental effect more likely. Also, the galactic center source began at least partially to unravel – the growth of the signal over time after the first discovery did not follow the expected trend but seemed rather compatible with a background fluctuation (see e.g. [91]).

A similarly strong challenge to the dark matter interpretation came from an updated analysis by the Fermi-LAT collaboration [92]. First, when taking the energy dispersion of the detector into account in the fitting, the signal significance decreases. Essentially, the signal is too narrow to be a genuine signal. In fact, a search in optimized ROIs over the whole energy range by the Fermi-LAT collaboration, taking into account the energy dispersion in the fitting, does not detect any significant lines at any energy above the 2σ level when accounting for all the trials factors [92]. Similarly important, when analyzing the Earth limb data – arising from the interaction of cosmic rays with the atmosphere – as a reference data set free of dark matter interactions shows a weak ($\sim 3\sigma$) line signal at 130 GeV for a certain range of incidence angles ($< 60^\circ$) in the detector [84]. Given that the expected Earth limb signal is a featureless powerlaw in that range [93] such a feature points towards an instrumental effect that preferentially reconstructs events at those energies. However, this (currently unknown) effect can only explain a minor fraction ($\sim 20\%$) of the galactic center signal. A second reference region (the galactic disk excluding the galactic center region) does not show such a feature at 130 GeV or at any other energy.

Given these complications, the current situation is such that there are some serious doubts about the origin of the signal, however, instrumental effects can also not fully explain the occurrence of the signal and therefore a dark matter origin remains a valid possibility. Future Fermi-LAT data will clarify the situation. A completely rewritten event reconstruction of the Fermi-LAT data that remedies several problems found after launch will enhance the energy resolution and will become available later this year (so-called *Pass-8*). If the signal remains significant with these updates, the Fermi-LAT management is considering an updated observing strategy that would enhance the exposure to the Galactic center. If the signal is not too extended ($\lesssim 2^\circ$ FWHM), the HESS-II array with its new 27-m diameter dish will have the required sensitivity to independently rule out or confirm the line at 130 GeV [94].

Future Searches and complementarity with other methods

In the absence of a space-mission that would improve the overall sensitivity over the Fermi-LAT significantly in the near future the community is looking toward the next generation ground-based instrument as the next big step in the indirect detection of dark matter through gamma rays[1]. The Cherenkov Telescope Array (CTA) is expected to start operation later in this decade (current start of construction planned for 2016) and will have sensitivity over the energy range from a few tens of GeV to 100s of TeV. To achieve the optimal sensitivity over that wide a range in energy, CTA will employ three different telescope sizes: Large Size Telescope (LST, 23 m diameter), Medium Size Telescope (MST, 10-12 m) and Small

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[1] it should be noted, that the planned Russian/Italian space-mission *Gamma-400* [102] aims to significantly improve the energy resolution which might be relevant for line searches

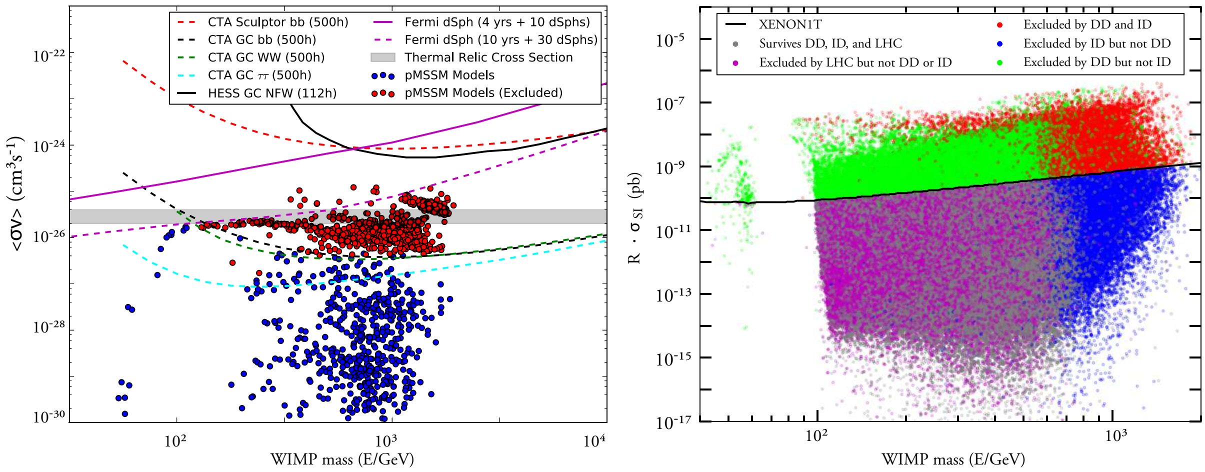

Fig. 2. **Left:** Reproduced from [95]. Comparison of current (solid lines) and projected (dashed lines) limits on the DM annihilation cross section from different gamma-ray searches as a function of WIMP mass. Limits for Fermi (magenta lines) and H.E.S.S. (solid black line) are calculated for a 100% branching ratio to bb (same as in Figure 1). Projected limits for CTA are shown for WIMP annihilation to bb and a 500 hour observation of Sculptor (red dashed line) and for WIMP annihilation to bb (black dashed line), W^+W^- (green dashed line), and $\tau^+\tau^-$ (cyan dashed line) and a 500 hour observation of the GC. For the sensitivity calculation of CTA the baseline array I [98] supplemented by a contribution of 36 mid-sized dual-mirror telescopes by the US groups is assumed. The calculation of the annihilation flux for the GC region assumes an NFW MW halo profile with a scale radius of 20 kpc and DM density at the solar radius of 0.4 GeV cm^{-3}. Filled circles represent pMSSM models satisfying WMAP7 constraints on the relic DM density and experimental constraints from ATLAS and CMS SUSY searches and XENON100 limits on the spin-independent WIMP-nucleon cross section [100, 101]. Models indicated in red would be excluded by the CTA 95% C.L. upper limit from a 500 hour observation of the Galactic Center. **Right:** Reproduced from [97]. Comparison of exclusion ranges for the three dark matter search strategies: direct detection (XENON1T and COUPP500 in green and red), indirect detection (CTA and Fermi-LAT in red and blue) and collider searches (LHC up to 8 TeV in magenta). Each dot represents a currently allowed pMSSM model in the plane of spin-independent cross-section versus mass of the lightest supersymmetric particle. Gray dots will not be detectable by any method.

Size Telescope (SST, 4-6 m). The design goal is a point-source sensitivity of at least an order of magnitude better than currently operating instrument at the sweet-spot of 1 TeV and a significantly improved angular resolution, improving with energy from 0.1° at 100 GeV to better than 0.03° at energies above 1 TeV. The US groups within the CTA consortium are planning to augment the array in the crucial mid-size telescope part. Current plans call for a doubling of the baseline number of mid-sized telescopes, enhancing the sensitivity by a factor of 2–3 [96].

Gamma rays are sensitive to almost any annihilation channel with a sensitivity that is closely related to the total annihilation cross section of dark matter that underlies its total relic abundance today. Already now, gamma-ray limits are probing below the thermal relic cross section for some of the preferred WIMP mass range. While direct detection experiments mostly have to deal with uncertainties in the background estimations, the indirect detection technique is largely dominated by astrophysical uncertainties. For dwarf spheroidal galaxies, these are largely mitigated by the lack of astrophysical backgrounds and tight constrains on the halo profile from dynamical measurements. For the galactic center these uncertainties are the largest but the prospects for a detection are still the highest. A positive (and credible) detection would entail either a gamma-ray line, like in the case of the aforementioned one at 130 GeV in the Fermi-LAT data or alternatively, from the measurement of identical spectra that are compatible with a dark matter origin from more than one source. None of the proposed dark matter search methods (direct detection, indirect detection or accelerator searches) will be able to unambiguously claim the detection of dark matter and thus all the methods are crucial in a viable dark matter program for the future. Each potential signal will potentially be created by a new (previously unknown) background – even in the case of accelerator searches. One big advantage of the indirect detection techniques is that if a signal is found in an accelerator or in a direct detector, gamma-ray measurements will provide the only way to connect the laboratory to the actual distribution of dark matter on the sky and identify the nature of the particle through the details of the annihilation process. In fact detecting a signal from the galactic center would allow to measure the dark matter density profile and feed back to cosmological simulations.

In addition, there is a unique region of the WIMP parameter space that CTA can best address in the near future – the high-mass ($\sim$ 1 TeV) scenario. Figure 2 (reproduced from [95] and [97]) shows the reach of CTA in currently-allowed pMSSM models as a function of the WIMP mass. The pMSSM (for *phenomenological* MSSM) is a 19-parameter model [99] that represents the most general version of an R-parity conserving MSSM subjected to experimental constraints. No assumptions are made about the physics of SUSY breaking within the pMSSM models. Therefore the pMSSM model set shows a much broader range of phenomenology than found in highly-constrained model sets. The left-hand graph shows the CTA sensitivity in the traditional representation in the $<\sigma_{\mathrm{ann}}v>$ WIMP mass plane (similar to Figure 1) for the $b\bar{b}$ annihilation channel overlaid with pMSSM models that saturate the thermal relic density (i.e. these particle constitute the bulk of the cosmological dark matter). The right-hand graph shows the same sensitivity, this time in the plane that is traditionally associated with direct-detection experiments, the spin-independent scattering cross-section σ_{SI} for pMSSM models without a constraint on the thermal relic density. As can be seen, CTA has significant reach in this model parameter space and is in particular uniquely suited to sensitively address WIMP masses around 1 TeV and above.

Conclusion

This is a exciting time for the search for dark matter. As the title of the NAS symposium suggests: we might be on the threshold of a discovery because our experimental and observational capabilities have progressed to the point where all three legs of the search for dark matter are sensitive to testing the WIMP paradigm in a very serious way. The LHC detectors are used to search for super-symmetric particles and will dominate the accelerator-based search for the next decade. The direct detection experiments are moving to ton-scale detectors and have taken great strides in improving their understanding of the backgrounds. And finally, indirect detection experiments, in particular using gamma rays, such as the Fermi-LAT, H.E.S.S., MAGIC, and VERITAS and the future Cherenkov Telescope Array (CTA) are starting to probe the thermal relic cross section in various astrophysical objects. While uncertainties about the dark matter profiles and the astrophysical foregrounds will always have a serious impact on the detectability of dark matter annihilation signals, the limits have gotten robust against these problems most recently. If lucky, we might even be able to measure the dark matter density profiles in the very inner parts of our galaxy or in dwarf satellites using gamma rays.

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