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High-energy gamma-ray sources of cosmological origin

Sources de rayons gamma de haute énergie d'origine cosmologique

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ABSTRACT

The current generation of instruments in gamma-ray astrophysics launched a new era in the search for a dark matter signal in the high-energy sky. Such searches are said indirect, in the sense that the presence of a dark matter particle is inferred from the detection of products of its pair-annihilation or decay. They have recently started to probe the natural domain of existence for weakly interacting massive particles (WIMPs), the favorite dark matter candidates today. In this article, we review the basic framework for indirect searches and we present a status of current limits obtained with gamma-ray observations. We also devote a section to another possible class of cosmological gamma-ray sources, primordial black holes, also considered as a potential constituent of dark matter.

RÉSUMÉ

La génération actuelle des détecteurs de rayons gamma d'origine astrophysique a ouvert une nouvelle ère dans la recherche d'un signal à haute énergie lié à la présence de particules de matière noire. Ces recherches dites indirectes, car on détecte les produits d'annihilation de deux de ces particules ou de leur désintégration, ont récemment commencé à sonder le domaine naturel des paramètres de l'hypothèse favorite : l'existence de particules de grande masse soumises seulement à l'interaction faible (*weakly interacting massive particles* ou WIMP). Dans cet article, nous rappelons le cadre de base des recherches indirectes, puis nous présentons l'ensemble des limites actuelles obtenues avec les observations gamma. Nous consacrons également une section aux trous noirs primordiaux, une autre classe de sources gamma d'origine cosmologique, discutée également comme candidat « matière » noire dans la littérature.

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1. The primordial soup as a source of energy

The investigation of the physics of the microcosm and of its role in the evolution of the Universe always requires the use of an energy reservoir. Contemporary researches in particle physics make use of powerful particle accelerators; this approach led to great successes with the building of the Standard Model of particle physics. The latest achievement in that field is the discovery of the Higgs boson that is responsible for the breaking of the electroweak symmetry and most likely describes how elementary particles acquire inertial mass. The Standard Model, although it reproduces hundreds of high-precision measurements, suffers from internal inconsistencies and lacks a microscopic description of phenomena observed on very large scales: dark matter (DM), dark energy, inflation. Another flaw of the model is its failure to offer a quantum description of gravitation. Challenging the Standard Model, with the idea of discovering what lies beyond it, is a task that requires either very high-precision measurements or access to an even more powerful energy reservoir, or both. A possible alternative to particle colliders lies in the use of natural environments to conduct particle physics experiments. Among other possibilities one can use stars or neutron stars to search for axions—those light particles that could explain the conservation of CP symmetry in strong interactions—, or the environment of supermassive black holes. The latter are used in gamma-ray observations of blazars to search for axions or for the breaking of Lorentz invariance (see [1] in this volume).

In the present article, we review some investigations that make use of the tremendous energy density that the first stages of the big bang may have offered. The study of the thermal history of the early universe has shown great success. For instance, at energies of the order of atomic bindings, the description of the physical phenomena that took place allows a very precise description of the recombination era, that is used as a tool for cosmology with the success that we know. At higher energies, the knowledge of the temperature and density evolution allows the rate of the nucleosynthesis of He and Li to be computed quite accurately. In this review, we go back even farther in time, and consider a hypothetical dark matter particle that would have been in thermal equilibrium at some point in the early universe. This scenario is very well motivated by both cosmological measurements and particle physics models, and it has triggered a lot of experimental research. Other interesting phenomena that could have happened in the very first stages of the evolution of the universe are relevant to gamma-ray astronomy. For example, very little is known about the fluctuation spectrum of matter at very small scales. Primordial black holes (PBH), of small mass compared to their cousins born in cataclysmic stellar deaths, may populate this part of the parameter space. Their evolution would entail a very slow mass loss through the Hawking–Bekenstein evaporation mechanism, ending in an explosive phase that would feature the emission of a flash of gamma rays. In some range of PBH initial mass, the final explosion could occur in the local universe and at the present time, making these photons potentially observable with gamma-ray telescopes.

In this article, we focus mainly on the role that gamma-ray observations play in the search for new phenomena related to the physics of the early Universe. It is organized as follows: the first section presents the status of PBH search in gamma-ray astronomy, while the remaining of the paper is devoted to searches for dark matter particles. In Sec. 3, a description of the evaluation of the relic density is presented, and some examples of particle physics models with dark matter candidates are summarized. In Sec. 4, we derive the expected gamma-ray signals. In Sec. 5, we review the searches for different types of targets with both satellite-borne and ground-based telescopes. Sec. 6 presents the specific case of the search for monochromatic lines, and Sec. 7 discusses the case of decaying dark matter. Finally, Sec. 8 gives a short update on future searches and on other means to search for particle dark matter. This article aims at providing a pedagogical introduction to the field, and relevant references are given for the reader who would like to go into further details. A very recent review, with a more in-depth discussion of the topic presented here, can be found in [2].

2. Primordial black holes

Black holes are called primordial when they are not formed by the gravitational collapse of a star, but rather by density perturbations during the early stage of the expansion of the Universe. Their initial mass scales as $M(t) \approx 10^{15}\ \mathrm{g} \times (t/10^{-23}\ \mathrm{s})$ with the time t elapsed since their creation after the Big Bang. Due to the Hawking–Bekenstein radiation, PBHs evaporate in a time $\tau \approx 400\ \mathrm{s} \times (M/10^{10}\ \mathrm{g})^3$, so that PBHs in the last stages of their lifetime at the current epoch were created at a time close to 10^{-23} s after the Big Bang, and thus with an initial mass of order 10^{15} g. Likewise, PBHs with mass greater than 10^{15} g would still survive at the present epoch and thus could be a potential dark matter candidate. Gamma-ray emission from PBHs could contribute to the extragalactic gamma-ray diffuse background via the cumulative emission over cosmic ages, with a photon spectrum peaking at 100 MeV at present days [3]. In addition to this observable, the theory predicts an explosive final stage for each black hole with a flash of very-high-energy gamma rays.

2.1. Constraints from gamma-ray diffuse emission

As the photon spectrum of evaporating black holes peaks at about 100 MeV, the cumulative emissivity of PBHs, up to the mass of those that would complete their evaporation at the present epoch, sums up to yield an expected isotropic gamma-ray signal that can be tested against the measured extragalactic background (EGB). This constitutes in fact one of the earliest constraints published [4], already restricting the averaged density Ω_{PBH} normalized to the critical density[1] to

[1] $\Omega_{\mathrm{PBH}} = \rho_{\mathrm{PBH}}/\rho_c$ where the critical density ρ_c is given as a function of the gravitational constant G and of the Hubble constant H_0 as $\rho_c = 3H_0^2/(8\pi G)$.

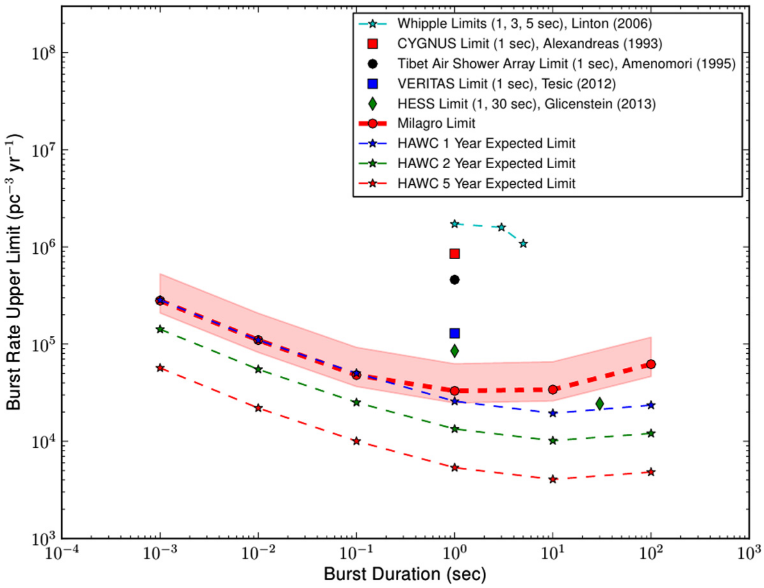

Fig. 1. Upper limits on the flash rate from gamma-ray observations performed on different time scales (figure from [13]).

be less than $\approx 10^{-8}$. This limit has been improved using EGRET, and Fermi-LAT data (see [5] for a review on the subject and [6] for an introduction to space-borne gamma-ray instruments), down to a few 10^{-9} if contributions to the EGB from astrophysical sources are taken into account. As these constraints do not include any enhancement effect from possible clustering, it may be legitimate to consider the Galactic diffuse emission [7] to derive constraints based on a halo model for PBHs that follows the same profiles as used in dark matter searches (see Sec. 3). This has been done with EGRET data in [8], with the result:

$$\Omega_{\rm PBH}(M = 5 \times 10^{14}\ {\rm g}) < 2.4 \times 10^{-10}\ {\rm to}\ 2.6 \times 10^{-9}$$

depending on the chosen Galactic halo profile. In summary, gamma-ray data are incompatible with a significant PBH contribution to DM, for initial masses in the range 10^{14}–10^{15} g.

2.2. Detectability of final flashes of PBH evaporation

One remarkable prediction of PBH evaporation is the possibility of an explosive final stage at energies that could reach several TeV. Note that these gamma-ray flashes have nothing in common with gamma-ray bursts in terms of luminosity: although emission from PBHs could be detected from within 30 pc or so, gamma-ray bursts have been observed up to redshifts of $z = 8$. Though this prediction of a final flash is somewhat model-dependent, several imaging atmospheric Cherenkov telescopes (IACTs) [9] have searched for clusters of photons coincident in time, using a sliding window technique with sizes from 1 to 30 s, as the correct time range is undetermined. In the past 10 years, upper limits on the rate of local PBH explosions have thus been derived with data from the Whipple observatory [10], VERITAS [11], H.E.S.S. [12], and very recently from MILAGRO [13]. The best limits so far reach about 4×10^4 pc^{-3}yr^{-1}, and a factor $\sim$10 improvement is predicted [13] with five years of HAWC operations [9,14]. While these constraints are much weaker than others derived from antiprotons or extragalactic and galactic gamma rays, as far as the relic density of PBH is concerned, they are still relevant from the perspective that the PBHs could be clustering in the Galactic halo, much like a dark matter component, potentially enhancing the local flash rate by several orders of magnitude. Fig. 1 shows the limits on the flash rate for different time scales obtained by several gamma-ray observatories.

2.3. PBH as gravitational lenses

Inasmuch as PBHs constitute a class of compact objects, they could reveal their presence through the gravitational lensing of cosmological sources [15], in the milli-, micro-, pico-, or femto-lensing regime, where the prefixes correspond to the scale of the angular separation in radians of the lensed images. Gamma-ray bursts (GRBs, see [16] in this volume) have proved to be useful to derive constraints in each regime. Given the limited angular resolution of gamma-ray telescopes (see [6] for a review), lensed images of the same object cannot be spatially resolved. One then resorts to comparing the time variability of two successive GRBs, and looking for identical patterns in these temporal "light curves".

For the milli-lensing regime that corresponds to a mass range from 10^{36} g to 10^{39} g and a time delay of order 1 to 10^4 s, PBHs are non-evaporating and cannot account for a sizeable fraction of dark matter in the Universe, due to the constraints coming from the cosmic microwave background [17]. They are still interesting objects from a fundamental perspective, and [18] provided mild limits in this mass range, based on an auto-correlation analysis of the first 44 GRBs from BATSE [19]. The micro-lensing regime, with masses of order 10^{24} to 10^{36} g, has been severely constrained by the MACHO and EROS experiments [20,21]. To the best of our knowledge, this mass range has not been covered by gamma-ray analyses. Pico-lensing operates on masses from 10^{18} to 10^{23} g and time delays of order 10^{-18} s. In this regime, magnification differences between the signals recorded by two detectors separated by at least 1 Astronomical Unit (average Sun–Earth distance), as was the case with BATSE and Ulysses [18], is better suited than autocorrelation analyses. The resulting limits obtained by comparing amplitudes of peak emissions for 60 bright bursts are very weak though, and the whole mass range was considered unconstrained by [17], until a recent analysis excluded a significant fraction of PBH dark matter contribution in this mass range from interactions with neutron stars [22,23]. Finally, in the range 10^{14} to 10^{18} g, and time delays of order 10^{-24} s, interference patterns in the energy spectrum can appear to emulate broad absorption and emission features.[2] Nevertheless, one should keep in mind that, in this mass range, PBHs cannot account for dark matter in the local Universe as they would have evaporated by now. In [18], it is ruled out at 95% confidence level (C.L.) that PBH in this mass range could contribute to $\Omega_{\rm PBH} > 0.1$ or 0.2, if the average redshift of GRBs is 2 or 1, respectively. More recently, [24] used Fermi GBM-detected bursts with known redshifts to improve these femto-lensing constraints by a factor 4, reaching a 95% C.L. upper limit of $\Omega_{\rm PBH} \sim 0.03$ at 3×10^{18} g.

3. Particle dark matter and its relic density

The relevance of the gamma-ray band to the searches for dark matter has to do with the mechanism through which the cosmological density of dark matter particles is fixed. In this section, we summarize the main motivations for searching for a dark matter signal with gamma-ray telescopes. A candidate dark matter particle must be massive, with weak interactions and sufficiently long-lived in order to keep its density constant over a large fraction of the age of the Universe. Such particles are predicted by some models of particle physics and are generically called "weakly interactive massive particles" (WIMPs).

After the Planck epoch very shortly after the Big Bang, the Universe is in an expansion phase. Due to the corresponding dilution of its constituents, the primordial plasma cools down while maintaining a global thermal equilibrium and undergoing different phase transitions. Let us assume that WIMPs are present in the early Universe. At very high temperature, when $kT \gg m$ where m is the mass of the dark matter particle, WIMPs are in equilibrium with the primordial plasma. Just like other species, their equilibrium density is set through self-annihilations:

$$\chi + \bar{\chi} \rightleftarrows A + \bar{A} \tag{1}$$

where χ is a dark matter particle and A is a standard-model particle. For most results presented in this article, the WIMP is assumed to be its own antiparticle ($\chi \equiv \bar{\chi}$), as predicted by popular models.[3] Let $n_{\rm eq}$ be the equilibrium density, then, in this high-temperature phase, the density follows a radiation-like dilution law $n_{\rm eq} \propto T^4$. As the temperature drops, a point is reached when the available thermal energy is too low to produce a pair of WIMPs in a collision of standard particles, whose masses are significantly lower. Then, the equilibrium is modified, and the density decreases as:

$$n_{\rm eq} \propto (m\,T)^{3/2} \times \exp\left(-\frac{mc^2}{kT}\right) \tag{2}$$

However, because of the expansion, the density n of WIMPs becomes too low for each particle to find a partner to annihilate with. Its evolution with time t is described by the following Boltzmann equation:

$$\frac{\mathrm{d}n}{\mathrm{d}t} = -3\,H\,n \;-\; \langle \sigma v \rangle \left(n^2 \;-\; n_{\rm eq}^2\right) \tag{3}$$

where H is the expansion rate, and $\langle \sigma v \rangle$ is the velocity-averaged annihilation cross section.[4] Since the $n_{\rm eq}$ term decreases rapidly (cf. Eq. (2)), the $3H$ term gets eventually dominant, leading to a constant co-moving density of WIMPs. At this stage, these particles fill the Universe as a relic population, and act as dark matter. The transition between the two regimes, and thus the time of the freeze-out of the dark matter density, is mainly determined by the value of the annihilation cross section. If it is small, the freeze-out occurs early and the final dark matter density is large. If the cross section is large on the other hand, WIMPs annihilate efficiently before the freeze-out and the final dark matter density is low.

A striking fact comes with the consideration of orders of magnitudes. Particles with masses around the electroweak scale ($\sim \Lambda = 200$ GeV)[5] and with weak interactions, are very well motivated theoretically. Considering a particle of mass m annihilating by exchanging states of masses $\sim \Lambda$, an order-of-magnitude estimate of the annihilation cross section[6] is

[2] See Fig. 2 in Ref. [24] for a simulation nicely illustrating the patterns in a femto-lensed GRB spectrum.

[3] Such a neutral particle identical to its antiparticle is called a "Majorana particle". Should it not be the case, the expected signal would be reduced by a factor of two and it is assumed in the following that the matter–antimatter asymmetry does not affect dark matter in that case.

[4] The annihilation rate is the product of $\langle \sigma v \rangle$ with the squared dark matter density.

[5] This scale, which determines the masses of the weak bosons is fixed by the vacuum expectation value of the Higgs field, namely 246 GeV.

[6] We assume here $m = 100$ GeV; $\alpha_{\rm W} = 1/30$ is derived from the weak coupling strength as $g_{\rm W}^2/4\pi$.

given by $\langle \sigma v \rangle \sim \mathcal{O}(\alpha_W) \times (m^2/\Lambda^4) \times \hbar^2 c^3$, i.e. a few 10^{-26} $\text{cm}^3\cdot\text{s}^{-1}$. When this typical value is injected into the Boltzmann equation (Eq. (3)), one ends with a dark matter density in the present-day Universe of the order of $\Omega_{\text{DM}}h^2 \simeq 0.1$, whereas the value inferred from astrophysical measurements is 0.11. This is a very intriguing fact as, in principle, the dynamics of the expansion of the Universe (through the value of H and n_{eq}) has nothing to do with the electroweak scale. This might just be a numerical coincidence but it is actually regarded by particle physicists as an invitation to test this scenario. It tells us that if a massive particle with weak interactions was in thermal equilibrium sometime in the early universe, then it is very natural that the remaining density be at the level of the measured dark matter density. This works for particles with masses between a few GeV [25] and a few hundreds of TeV [26].[7] This scenario provides a clear physics case: the mass range is fixed and there is a target value for the annihilation cross section.

From the point of view of particle physics, the building of models in which the electro-weak symmetry is naturally broken requires new massive particles with weak–scale interactions. If one of these is stable, it could well be the dark matter particle, according to the scenario described above. One famous example is the hypothetical neutralino, which is a linear combination of supersymmetric partners of gauge and Higgs bosons [27]. Other popular models consider extra dimensions. A photon traveling through space with an additional compact dimension can explore this extension when its wavelength is comparable to the size of the extra dimension. If the corresponding state is protected by a discrete symmetry, then the photon trapped in the extra space would be interpreted as a massive particle by observers only sensitive to the usual dimensions [28,29]. This is a very simple way to build a WIMP model from standard model fields.

While WIMPs are by nature very elusive, they could be produced in accelerator experiments such as ATLAS or CMS at the Large Hadron Collider. Their presence is then usually derived from detailed comparisons of data with Monte-Carlo simulations in some topological channels. These searches (see [30,31] for recent results related to the WIMP hunt) can point to the characteristics of a WIMP candidate, but only observations of the cosmos can identify such a candidate as the dark matter constituent. One way to achieve this goal is to search for the presence of dark matter in the vicinity of the Earth by detecting elastic collisions of WIMPs on atomic nuclei. The effects of their recoil are searched for using heat, ionization or scintillation. In contrast to these so-called "direct" experiments (see [32,33] for further details), "indirect" searches rely on the expectation that WIMPs annihilate in pairs or decay, and attempt to detect the resulting flux of Standard Model particles.

4. Expected signals in the gamma-ray band

After the freeze-out of their cosmological density, dark matter particles cluster under the effect of gravitation and form structures, at the centre of which the galaxies form after photons decouple from baryonic matter. Dark matter halos are spherically symmetric, with a dense inner part and many subhalos. The typical extent of a dark matter halo like the one in which the Milky Way is embedded is about ten times larger in radius than the disk containing stars. The distribution of dark matter in Milky-Way-sized galaxies is estimated with numerical simulations of structure formation (*e.g.*, [34,35]). These simulations are constantly evolving and still some intrinsic uncertainties remain, in particular in the description of the dark matter density at small scale. The shape of the dark matter halo is predicted to be scale-invariant. This property is probably broken at sub-galactic scale due to the influence of baryons, or to the presence of supermassive black holes in the centre of galaxies. Various halo shapes are used in dark matter signal searches, and the reader should refer to the quoted papers for details. However, three very common halo density parameterizations are the Navarro–Frenk–White profile (NFW, [34]), the Einasto profile [36,37] and the isothermal profile [38], given respectively by:

$$\begin{aligned}\rho_{\text{NFW}}(r) &= \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2} \\ \rho_{\text{Einasto}}(r) &= \rho_s \exp\left(-\frac{2}{0.17}\left[\left(\frac{r}{r_s}\right)^{0.17}-1\right]\right) \\ \rho_{\text{iso}}(r) &= \frac{\rho_s}{1+(r/r_s)^2}\end{aligned} \tag{4}$$

Each halo is described by two parameters: a characteristic radius r_s and a normalization factor ρ_s directly related to the density at radius r_s.

In the examples shown in the next sections, some uncertainties on the obtained limits come from the choice of the halo profile and the choice of the set of parameters. In the central regions of halos and subhalos, the dark matter density can be high enough for the annihilation to proceed efficiently. Since the relative velocity of dark matter particles is small in our Galaxy, WIMPs are non-relativistic and their annihilations would convert most of the dark matter mass into kinetic energy of standard particles. All sorts of usual particles can be created in such a process, but, unless the annihilation goes directly into neutrino pairs, the processes eventually lead to the production of photons with energies up to the mass of the

[7] Note that the case for smaller cross sections needs not be considered within this scenario, since the associated dark matter density would be too large.

dark matter particle. These photons are generated during the hadronization and decays of the annihilation products. The gamma-ray flux from dark matter annihilations can be generically written as:

$$\Phi_{\rm DM} = \frac{{\rm d}N}{{\rm d}E}(E)\,\frac{\langle\sigma v\rangle}{m^2}\,\frac{1}{4\pi}\int_{\Delta\Omega}{\rm d}\Omega\int_{\rm los}\frac{\rho^2}{2}\,{\rm d}\ell \tag{5}$$

where the first factor is the gamma-ray annihilation spectrum, and the last integrals are computed over the line of sight and the solid angle. If the annihilation volume is fully contained in the observed region within $\Delta\Omega$, it reduces to $1/D^2 \times \int(\rho^2/2)\,{\rm d}V$, where D is the distance to the considered dark matter region, and the last integral represents the number of annihilations within the considered target volume.[8] The ${\rm d}N/{\rm d}E$ term depends on the assumption made for the annihilation channels, so that $\langle\sigma v\rangle$ is the velocity-weighted annihilation cross section, whose natural value is of the order of $3 \times 10^{-26}\ {\rm cm}^3{\cdot}{\rm s}^{-1}$ according to the above-described scenario. The usual way to search for dark matter starts with the modeling or some astrophysical measurement of the dark matter distribution in some region. This can be done for example using numerical simulations of dark matter clustering or using star kinematics within the targeted object. In the absence of signal, an upper bound on $\Phi_{\rm DM}$ is derived and Eq. (5) can be inverted to obtain exclusion limits in the $\langle\sigma v\rangle$–m plane. In the following sections, a review of the present constraints is given.

5. Searches for WIMPs through gamma-ray observations

In the framework of indirect searches, gamma rays offer many advantages over charged particles such as antiprotons or positrons: they are not deflected by cosmic magnetic fields, so that their source is well localized in the sky, nor do they undergo much attenuation. The generic difficulty is the presence of a rich and complex astrophysical background due to gamma-ray sources and a large-scale diffuse emission. Since its launch in 2008, the Fermi-LAT has played a major role in bringing WIMP gamma-ray searches to the forefront, together with current-generation Cherenkov instruments [9] H.E.S.S., VERITAS and MAGIC. This section presents a short summary of the constraints that null detections have imposed on the $\langle\sigma v\rangle$–m plane, corresponding to the fundamental WIMP parameters in Eq. (5). In this review, we only gather results on annihilation limits, leaving for section 7 a discussion of constraints on decaying WIMP models. We also illustrate the limits, whenever possible, with the results obtained in the $b\bar{b}$ annihilation channel[9] with a NFW profile (see Sec. 4), for the sake of uniformity. Most publications cited in the text present results for other channels and profiles as well.

5.1. Milky Way and local group

For a given WIMP model, Eq. (5) clearly points to the two critical features allowing for a strong expected flux: closeness to the "locus" of annihilation (the distance D) and a large expected WIMP density (the term ρ^2 integrated along the line of sight). In this regard, the Milky Way itself, and its closest satellites, are *a priori* the best targets for gamma-ray searches.

5.1.1. Galactic centre signal and galactic halo analysis

If the scenario described in the preceding sections is correct, our Galaxy should be embedded in a dark matter halo, with an increased density in the central region of the Galaxy, which also hosts a supermassive black hole. As a result, and despite the complexity of baryon–dark matter interactions in this neighborhood, the Galactic Centre has long been the primary focus of indirect searches [39,40]. Between 2004 and 2006, this region was observed by H.E.S.S. with unprecedented sensitivity. A powerful TeV source (HESS J1445-290) was detected [7]. On the basis of an analysis of the energy spectrum [41], it was shown that the emission could not be entirely due to a WIMP heavier than 200 GeV. On the other hand, it represents a background for any analysis attempting to detect dark matter annihilation at the very centre of the halo. Experimental teams then turned to the observation of the immediate surroundings of this source, where conventional emission is less present. Recently, using Fermi-LAT data, several groups claimed the detection of a GeV excess at the Galactic Centre (e.g., [42]), that is visible when the contribution of the Galactic diffuse emission (estimated by a model) and that of local point-like sources are subtracted from the data (see also [7]). Unfortunately, these two background components are not easy to model in a robust way. First the Galactic diffuse emission is notoriously strong in this region, while its modeling is increasingly difficult due to degeneracy in gas velocity determination and imprecise optical photon field estimations in this highly obscured region. Second, the source population below the LAT angular resolution is not precisely known, as can be witnessed by the discussion around potential millipulsar contribution, not to mention the fact that the central gamma-ray source detected by the LAT (2FGL J1745.6-21858) and Cherenkov telescopes (HESS J1445-290) has been interpreted in relation with the presence of a local population of cosmic rays [7]. Furthermore, it is worth noting that a definitive study of the Fermi bubbles [7] at low latitude is still missing, which may bear an impact on this discussion. As a consequence, early-on alternative strategies have been devised in order to retain the advantage of the high expected flux in the direction of the Galactic Centre, while avoiding the centre itself [43]. H.E.S.S. and Fermi-LAT collaborations took this course of action with

[8] If the dark matter particle is not its own antiparticle then an additional factor of two appears at the denominator

[9] b is the "beauty" or "bottom" quark.

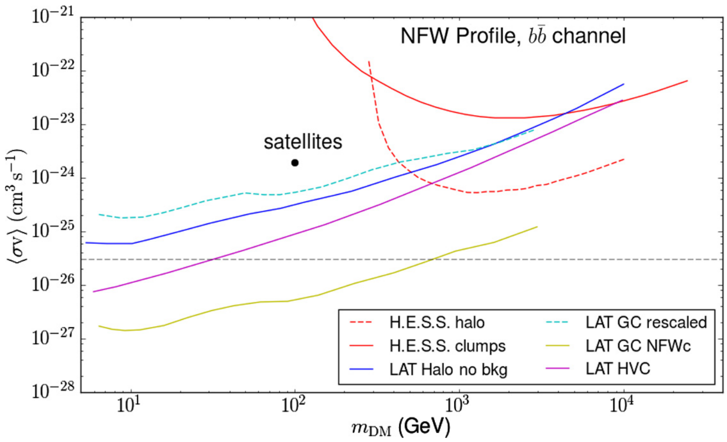

Fig. 2. Upper limits (UL) on velocity-averaged annihilation cross section from indirect searches in γ rays, for analyses focusing on targets inside the Milky Way. In red ("H.E.S.S. clumps"), exclusion curves on a signal coming from subhalos with H.E.S.S. data [49]; in dashed red ("H.E.S.S. halo"), 3σ upper limits in the Galactic Centre halo analysis from [44]; in red ("LAT halo no bkg"), the LAT halo analysis [45] corresponding to the same 3 standard deviation confidence level (3σ C.L.) upper limits, when no diffuse background modeling is performed; in cyan ("LAT GC rescaled"), the LAT diffuse-model-free 3σ upper limit at the Galactic Center [46], rescaled to the same local dark matter density as the LAT halo analysis; in yellow ("LAT GC NFWc"), same but in the case of a contracted NFW profile; in magenta ("LAT HVC"), the 95% C.L. limits obtained with the Smith cloud [50]. The dot marker with the label "satellites" corresponds to the 95% C.L. upper limit for a 100 GeV WIMP mass obtained in the unidentified LAT source analysis [51]. The natural scale for the dark matter annihilation cross section is displayed as the horizontal dashed line. Figure adapted from [2].

an analysis of the close vicinity of the Galactic centre for H.E.S.S. and of a larger sky area for the LAT. The results, published in [44] and [45], are shown in Fig. 2. An alternative route is to consider the whole emission as originating from a dark matter signal, and to infer extreme (in the sense of overly conservative) limits on a WIMP contribution, as in [46]. As can be see in Fig. 2, such an analysis is hardly competitive, unless one assumes an extremely spiky inner profile of the dark matter halo. For the sake of exhaustivity, we also report in Fig. 2 the null result from an early search for a WIMP signature in the LAT unidentified sources of the first point source catalogue [47], and a recent result derived from the null detection of a local High-Velocity Cloud (HVC), which yields competitive results with the halo analysis. But the dark matter content of such HVCs is highly controversial [48]. In summary, while the Galactic centre region remains a "holy Grail" for dark matter indirect searches, recent claims of detection of an excess that could be compatible with a WIMP signal clearly need an independent detection to turn this claim into a discovery. The next closest targets, the dwarf spheroidal galaxies orbiting the Milky Way, may well play this role.

5.1.2. Searches for dark matter clumps

The next step in scales of possible targets leads to dark matter clumps. The formation of the Milky Way proceeded through the merging of smaller halos. In principle, most of them are far from the Galactic disk and should remain in the dark matter halo as relics of our Galaxy's assembly history. While it is possible to search for such substructures, one difficulty is that they should not contain baryons, as they are far from the disk and potentially too light to have accreted gas. Having no stars, their locations remain unknown. Searches for clumps can be performed with unbiased γ-ray surveys of the sky. If unidentified sources are found and ruled out as dark matter sources (from morphology, spectrum, variability), then it is possible to rule out some WIMP parameters. These analyses are based on estimates of the probability to have a clump in the surveyed field, and rely on numerical simulations of the formation of Milky-Way-sized galaxies [52]. Such analyses have been conducted using Fermi-LAT data and the H.E.S.S. survey of the Galactic plane. In [53] and [49], exclusion curves are derived, also shown in Fig. 2.

5.1.3. Dwarf spheroidal galaxies around the Milky Way

Together with the Galactic Centre, the spheroidal dwarf galaxies orbiting the Milky Way are the best targets for indirect dark matter searches with gamma rays. Indeed, they are vastly dark-matter dominated, according to the kinematics of their member stars, most of them are practically devoid of any gas, and thus are not expected to harbor the typical astrophysical processes yielding high-energy photons. While LAT initial results with one year of data [54], and imaging atmospheric Cherenkov telescopes (IACTs) observations with sufficiently long observing times [55,56], already showed the potential strength of these targets, an important breakthrough occurred when the different dwarf galaxies were analyzed with a joint likelihood technique, generalized to account for statistical uncertainties in modeling the dark matter content from stellar data. This combined analysis proves particularly powerful with an all-sky surveyor like Fermi-LAT [57–59], but has recently been successfully applied by the H.E.S.S. collaboration as well [60].

Fig. 3 summarizes the current status of upper limits obtained with analyses toward the Segue 1 dwarf spheroidal galaxy, arguably the best dwarf target so far. In addition, the figure shows combined limits published separately by Fermi-LAT and H.E.S.S. These limits on dwarf galaxies are compared with those obtained by H.E.S.S. on the Galactic halo (the present best

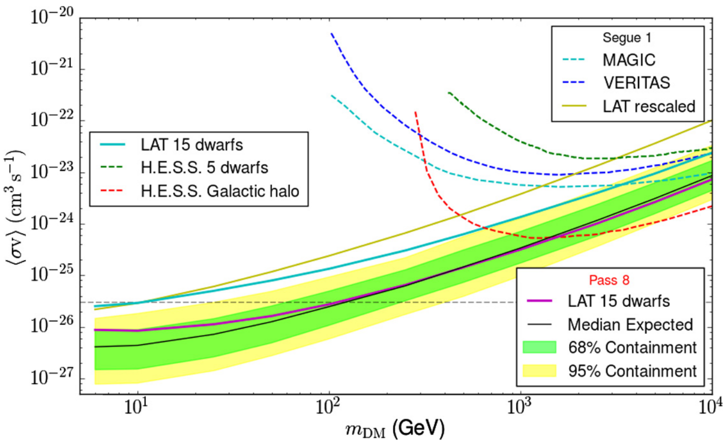

Fig. 3. Exclusion limits on velocity-averaged annihilation cross section reached by gamma-ray observations in the direction of dwarf spheroidal galaxies. The continuous lines correspond to LAT observations, while the dashed lines correspond to IACT observations. The cyan, blue, and yellow curves labeled in the top right panel present limits obtained with Segue 1 only, respectively with MAGIC [64], VERITAS [65], and Fermi-LAT [58]. In the case of the LAT, the curve shown has been obtained with the same dark matter spatial distribution as in [65], and thus is directly comparable to it. Next, the curves labeled on the middle-left panel presents the best limits so far when performing a combined analysis with 15 dwarfs in the case of the LAT (in blue, [58]) and 5 dwarfs in the case of H.E.S.S. (in green, [60]), together with the current best IACT limits, obtained with a H.E.S.S. analysis of the Galactic halo in the vicinity of the Galactic center [44]. Finally, the bottom-right panel labels the curves recently derived by the LAT team with the same dwarfs as in [58], but the updated and improved so-called "Pass 8" dataset [61]: the limits in magenta are compared with the 68% and 95% bands estimated from 300 random sky positions, and the corresponding median expected limits in thin black dashed line. The natural scale for the dark matter annihilation cross section is displayed as the horizontal grey dashed line. Figure adapted from [2].

limit from IACTs), and the recent results obtained by the Fermi-LAT collaboration with the new version of the reconstruction and event-analysis pipeline dubbed "Pass 8" are also shown for comparison [61]. It is worth noting that MAGIC constraints are obtained with 160 hours on target, compared to 48 h for VERITAS and 4 years of nominal LAT survey for the LAT rescaled curve. While it seems that the IACTs become competitive above 1 TeV, the combined limits obtained with H.E.S.S. are derived from modest observation times toward Coma Berenices (8.6 h), Fornax (6.1 h), Carina (23.2 h), and Sculptor (12.5 h), all having estimated dark matter content far lower than Segue 1. Deeper observations have the potential of further improvements. The H.E.S.S. limits also include 90 h on Sagittarius, but the initial constraints presented in [62] have been revised to much lower values in [63]. Nevertheless, the resulting combined limit shows the power of performing such a joint likelihood technique, which could also be used to combine data from different experiments. The results could eventually become competitive with the H.E.S.S. analysis of the Galactic Centre halo.

To conclude this section, it appears that $\langle \sigma v \rangle$ in excess of 10^{-25} cm^3·s^{-1} is now ruled out at 95% confidence level over the WIMP mass range from 5 GeV/c^2 to ∼1 TeV/c^2.

5.2. Galaxy clusters and global cosmological signal

5.2.1. Galaxy clusters

The approximate dynamical equilibrium reached by several if not all galaxy clusters has long been known to be in tension with the matter budget in galaxy members and intra-cluster gas, as inferred from optical and X-ray observations. The estimated amount of dark matter would turn these objects into major targets for indirect searches, if not for 3 caveats. First, while the closest clusters are the most appealing targets, their angular size on the sky is very large, rendering gamma-ray analyses difficult. One could instead try to focus on the inner region of the cluster, but this quickly degrades the sensitivity, with the additional problem that a cluster may have a gamma-ray shining active galaxy in its inner region, as exemplified by the active galaxy M87 in the Virgo cluster. Second, the determination of the dark matter density profile, which needs to include subhalo contributions, is hard to achieve. Third, galaxy clusters are actually expected to shine in gamma rays from standard astrophysical processes such as diffusive acceleration and radiation of local cosmic rays, and this emission has not even been detected so far.

Despite these difficulties, the Fermi-LAT and IACT collaborations have analyzed the data in direction of some of the closest clusters: upper limits have been published for Fornax and Coma by the H.E.S.S. and VERITAS collaborations, respectively, and the Fermi-LAT team has separately studied these two clusters, and then combined them – in much the same way as the dwarf spheroidal galaxies—with three other clusters, which yields the best upper limits published so far. These results are gathered in Fig. 4.

5.2.2. Global cosmological signal

As the annihilation gamma-ray signal is expected from all halos at all ages of the Universe, an isotropic component is expected from the integration of the emissivity of all the halos at all redshifts. This cosmological signal would add to the

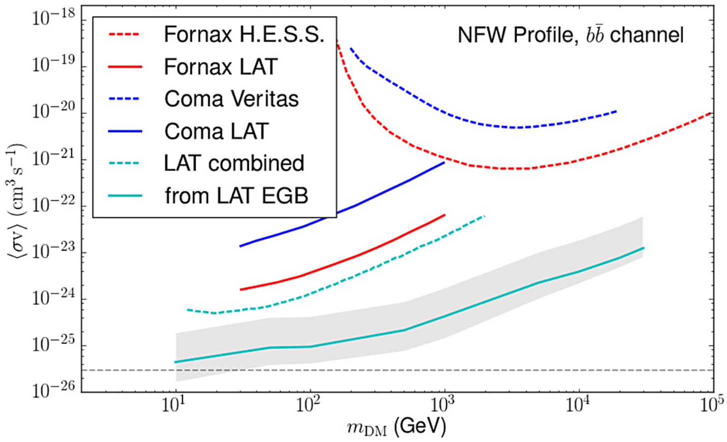

Fig. 4. 95% C.L. upper limits on velocity-averaged annihilation cross section obtained in the $b\bar{b}$ annihilation channel by several gamma-ray instruments looking at extragalactic targets. From top to bottom, limits on Coma with VERITAS [70], limits on Fornax with H.E.S.S. [71], Coma and Fornax limits obtained with the LAT [72], and combined LAT analysis of 5 clusters [73]. The bottom curve with the shaded area is the upper limit curve obtained for a cosmological signal [69], and its systematic uncertainty band arising from halo population modeling. The natural scale for the dark matter annihilation cross section is displayed as the horizontal dashed line. Figure adapted from [2].

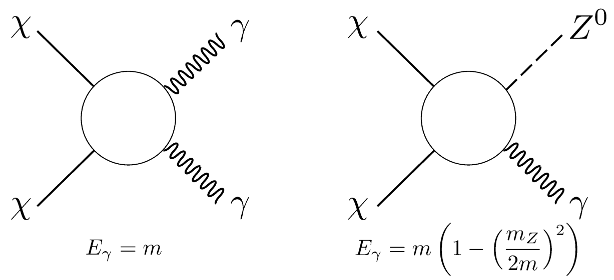

Fig. 5. Feynman diagrams for two loop-suppressed processes giving rise to gamma-ray lines, at the value E_γ, for a dark matter particle of mass m. When m is significantly higher than the Z-boson mass m_Z, the two gamma-ray lines merge into a single feature in gamma-ray spectra.

extragalactic background emission (EGB), which includes all the extragalactic sources resolved by the instrument, all the unresolved extragalactic sources, and all the truly diffuse emission. Such a search for a “cosmological signal” has recently been published by the Fermi-LAT collaboration, with an energy range from 100 MeV to 820 GeV and updated data sets and response functions [66]. It is then possible to compare the predicted spectrum of a cosmological signal from dark matter to the EGB, and infer constraints that are more or less conservative depending on whether one also attempts to account for the astrophysical component of the EGB [67,68] or not. In Fig. 4, the 95% C.L. limits recently published by [69] are presented, together with the band illustrating the uncertainties in subhalo populations within the halos, including the Galactic one. This figure is suggestive of the great sensitivity that such an analysis can provide, thanks especially to the LAT increasingly precise measurements of the EGB spectrum and extragalactic population contributions. It is worth noting that galaxy clusters suffer from fairly identical systematic uncertainties as the cosmological analysis, especially the extrapolation to very low subhalo masses that are not resolved by N-body simulations. Thus cluster limits are not expected to improve much compared to those on the cosmological signal, and their sensitivity is competitive only if a combined analysis is performed.

6. Line features

In case of a 2-body final state in the annihilation ($\chi+\chi\to\gamma+\gamma$ or $\chi+\chi\to\gamma+Z^0$), a monochromatic line at the WIMP mass, or close to it for WIMP masses slightly above the Z^0 mass, is expected. This loop-suppressed process, illustrated in Fig. 5 is allowed if direct annihilation into charged particles is possible. While loop suppression implies that the resulting process is very rare, there is no known astrophysical process that could mimic such a feature. As the velocity dispersion of a WIMP is negligible due to its mass, annihilations occur almost at rest, so that the sharpness of the line feature is expected to closely follow the resolution of the detector.

From the observation of regions with high dark matter concentration such as the Galactic Centre, spectral analyses have been performed on the Fermi-LAT data and the H.E.S.S. data. No significant line signal was found, yielding the exclusion curves obtained by H.E.S.S. [76] and Fermi-LAT [74], shown in Fig. 6. An important point of caution here is that the process

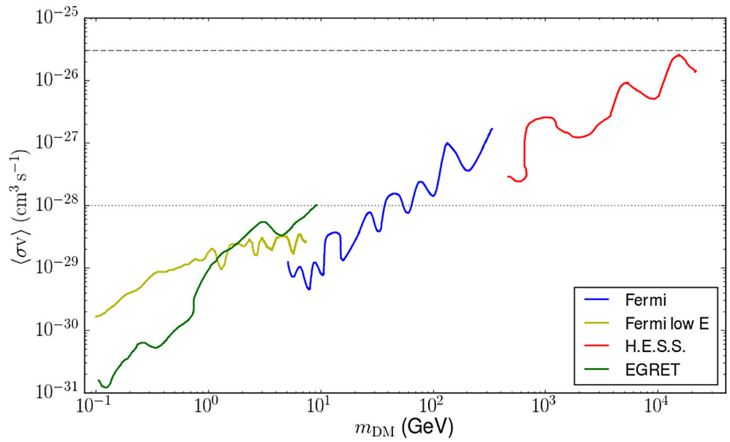

Fig. 6. Upper limits on velocity-averaged annihilation cross section into mono-energetic gamma rays derived by several instruments in searches for line features. Blue and yellow lines show the limits obtained with the Fermi-LAT in a first standard analysis [74] and in a dedicated low-energy follow-up [75], respectively. The red line shows the limits obtained by the H.E.S.S. collaboration [76]. For reference, the EGRET limits obtained by [77] are also shown. The natural scale for the tree-level dark matter annihilation cross section is displayed as the horizontal dashed line. The natural scale for gamma-ray line production is displayed as the horizontal dotted line. Figure adapted from [2].

of line production involves two additional weak couplings, so that the natural value for the annihilation into monochromatic photons is expected at or below 10^{-28} cm^3·s^{-1}. The experimental limit reaches this value below masses of about 50 GeV.

Note that it has been recently claimed that a gamma-ray line was observed close to the Galactic Centre with the data from Fermi-LAT [78], at an energy of about 130 GeV. Re-analysis of the dataset by the Fermi collaboration, illustrated in Fig. 6, rules out this possibility.

7. Decaying dark matter

An alternative to annihilating dark matter lies in the possibility that new particles, produced thermally during the big bang, would be unstable but with a lifetime larger than the age of the universe. In that case, decay of dark matter particles could produce high-energy radiation as well. While the annihilation is proportional to ρ^2, the decay signal depends here linearly on the dark matter density ρ as:

$$\Phi_{\rm DM} = \frac{{\rm d}N}{{\rm d}E}(E)\,\frac{1}{4\pi}\,\frac{\Gamma}{m}\int\limits_{\rm los}\rho(\ell)\,{\rm d}\ell \tag{6}$$

where the integral runs over the line of sight and Γ is the decay constant. If the decay constant is of the order of 10^{26} s, the dark matter signal could be sizable enough to be observable. For such a value, the decay rate is sufficiently long compared to the age of the universe, so that the dark matter cosmological abundance over the history of the Universe stays in agreement with observations [79]. Decay signals have been searched for with gamma-ray observations, both of the diffuse emission [80] and of specific sources [81]. Fig. 7 illustrates a possible constraint in the case where dark matter particles decay into $b\bar{b}$ quark pairs.

8. Future searches

With the important results reached by current-generation instruments during the past ten years, it is expected that next-generation gamma-ray telescopes will include indirect searches for a dark matter signal as one of their core topics. It is indeed the case with many projects introduced in [14] in this volume. Nevertheless, few have gone far enough as to make public preliminary studies of sensitivity. Fig. 8 shows a selection of such predicted limits from currently running experiments and future projects.

For instance, the LAT dwarf spheroidal analysis (in cyan) has been simply extrapolated to ten years of Pass 8 data and a factor 3 more dwarfs used, while VERITAS will reach by 2018 an unprecedented exposure time on Segue 1 (in magenta). Likewise, the yellow and blue curves show upper limits expected from an analysis close to the Galactic Centre by H.E.S.S. II and CTA, respectively. In the latter case, a more conservative discussion by [83,84] that attempts to take into account uncertainties in the Galactic diffuse emission is presented in green and black, respectively. Finally, the red curve shows the limits on Segue 1 resulting from one year science operation of the full HAWC array. It is worth reminding here that the HAWC duty cycle is much larger than for IACTs and that it surveys a large fraction of the sky, so that these limits will quickly improve with an increased dataset and combined analyses of several dwarf spheroidals. Broadly speaking, it seems

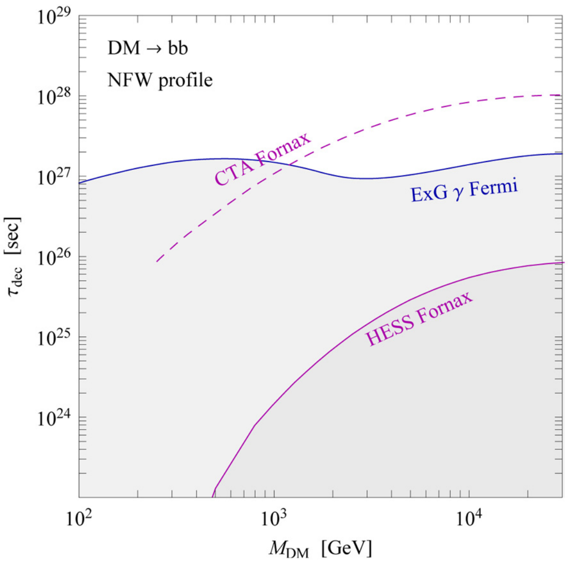

Fig. 7. Constraints on the decay constant of dark matter particles from gamma ray observations. Grey regions are excluded (figure from [81]).

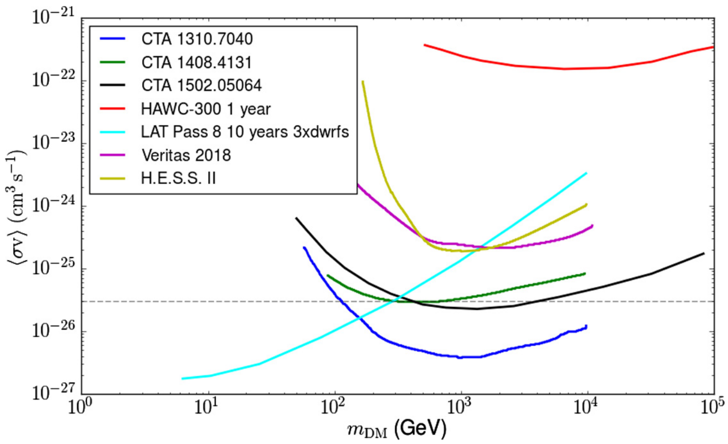

Fig. 8. Selection of some anticipated limits reachable with current or future experiments. The blue curve is from a Galactic Centre analysis with CTA [82]. The green curve comes from a similar analysis, but attempting to account for the degradation of the limits due to uncertainties in the Galactic diffuse emission [83]. Likewise, the curve in black [84] re-assess the expected sensitivity with an up-to-date evaluation of the uncertainties. The red curve corresponds to one-year of observation of Segue 1 with the full HAWC instrument [85]. The cyan curve shows the Fermi-LAT Pass 8 limits by 2018, accounting for more dwarf spheroidal galaxies, based on a preliminary analysis of 5 years of data. The magenta curve shows the VERITAS expectations from 1000 hours on Segue 1 [86], and the yellow curve is an estimate by [87] of the limits that H.E.S.S. II could reach with an analysis at the Galactic Centre. The natural scale for the dark matter annihilation cross section is displayed as the horizontal dashed line. Figure adapted from [2].

that the next decade will see the natural scale of $\langle\sigma v\rangle \approx 3.10^{-26}$ cm^3·s^{-1} completely covered at 95% C.L. over the [few GeV, few tens of TeV] mass range.

9. Conclusion

In the past two decades, gamma-ray astronomy has been instrumental in constraining exotic sources that would have their roots in some primordial cosmological processes. In particular, it provides some of the best constraints on microscopic black holes and particle dark matter candidates. While dark matter seems ubiquitous in the Universe at all scales, it still evades detection and identification as a particle beyond the very successful Standard Model. Nevertheless, we reviewed the field of indirect searches through gamma rays, which recently started to constrain the natural scale of annihilation that makes the “WIMP miracle” so appealing, when assuming that it is entirely a thermal relic. It is probably too early to move away from the thermal WIMP paradigm [88], though its supersymmetric incarnation starts to be “under siege” [89]. At any rate, indirect searches are largely complementary to direct searches, performed in the laboratory and looking for

DM particle scattering on active material, or collider searches at the LHC. In this respect, Run-2 analyses from ATLAS and CMS are awaited with deep interest. At the moment, it is worth noticing that the natural scale for the annihilation cross section has been reached by the sensitivity of Fermi-LAT. If the value of the thermal cross section is taken at face value, the observations of dwarf galaxies allow WIMPs with masses below ∼30 GeV to be excluded. Larger masses will soon be probed by the next generation gamma-ray observatory CTA.

Acknowledgements

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