Dark Matter: A Multidisciplinary Approach

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We review the current status of accelerator, direct and indirect Dark Matter (DM) searches, focusing on the complementarity of different techniques and on the prospects for discovery. After taking a census of present and upcoming DM-related experiments, we review the motivations to go beyond an "accelerator-only" approach, and highlight the benefits of multidisciplinarity in the quest for DM.

I. INTRODUCTION

The evidence for non-baryonic dark matter is compelling at all observed astrophysical scales [1, 2]. Although alternative explanations in terms of modified gravity (see Ref. [3] for a relativistic theory of the MOND paradigm) cannot be ruled out, they can hardly be reconciled with the most recent astrophysical observations [4] without requiring additional matter beyond the observed baryons (e.g. Ref. [5] and references therein). It is therefore natural to ask *how can we identify the nature of DM particles?*. We review here the main strategies that have been devised to attack this problem, namely accelerator, direct and indirect searches, focusing on the interplay between them and on their complementarity.

In fact, a tremendous theoretical and experimental effort is in progress to clarify the nature of DM, mostly devoted, but not limited, to searches for Weakly Interacting Massive Particles (WIMPs), that achieve the appropriate relic density by *freezing-out* of thermal equilibrium when their self-annihilation rate becomes smaller than the expansion rate of the Universe. The characteristic mass of these particles is $\mathcal{O}(100)$ GeV, and the most representative and commonly discussed candidates in this class of models are the supersymmetric neutralino, and the $\mathrm{B}^{(1)}$ particle, first excitation of the hypercharge gauge boson, in theories with Universal Extra Dimensions.

A tentative census of present and upcoming DM experiments (WIMPs only) is shown in fig. 1. Shown in the figure are: two particle accelerators, viz. the Tevatron at Fermilab, and the upcoming Large Hadron Collider (LHC) at CERN; the many direct detection experiments currently taking data or planned for the near future, along with the names of the underground laboratories hosting them; high-energy neutrino telescopes; gamma-ray observatories; gamma-ray and anti-matter satellites. Light blue points denote gamma-ray experiments that are not directly related to indirect DM searches, as DM signals would be typically produced at energies below their energy threshold. Nevertheless, they may turn out to be useful to discriminate the nature of future unidentified high-energy gamma-ray sources. Three satellites are shown in the inset of figure 1: PAMELA, an anti-matter satellite that has already been launched and is expected to release the first scientific data very soon. ; GLAST, a gamma-ray satellite that is scheduled for launch in early 2008; and AMS-02, anti-matter satellite that should be launched in the near future.

We will discuss below the prospects for detecting DM with the various experiments shown in fig. 1, and we will focus our attention on the complementarity of the various detection strategies. The paper is organized as follows: we first discuss accelerator searches, and show that although the LHC has the potential to make discoveries of paramount importance for our understanding of DM, it may not be able to solve all problems. In Section 3 we discuss the information that can be extracted from direct detection experiments, in case of positive detection. Section 4 is then dedicated to indirect searches, and to the question of what astrophysical observations can tell us about the nature of DM, and how to combine this information with all other searches.

II. COLLIDERS MAY NOT BE ENOUGH

The Large Hadron Collider (LHC), which is about to start operations at CERN, will allow us to explore possible extensions of the Standard Model of particle physics, reaching a center-of-mass energy of about 14 TeV. Obviously, the discovery of new particles would be of paramount importance also for Astrophysics and Cosmology, and would represent a big step forward in our understanding of the Universe. However, as we argue below, it will not be easy to extract, from accelerator experiments alone, enough information to unambiguously identify DM particles.

The constraints that can be placed on a dark matter candidate from collider experiments are strongly model-dependent, and it is, unfortunately, impossible to describe the reach of colliders in their search for dark matter in any kind of general way. However, a number of searches for particles associated with a dark matter candidate already provide interesting constraints on proposed extensions of the Standard Model of particle physics, and they include studies such as: invisible Z

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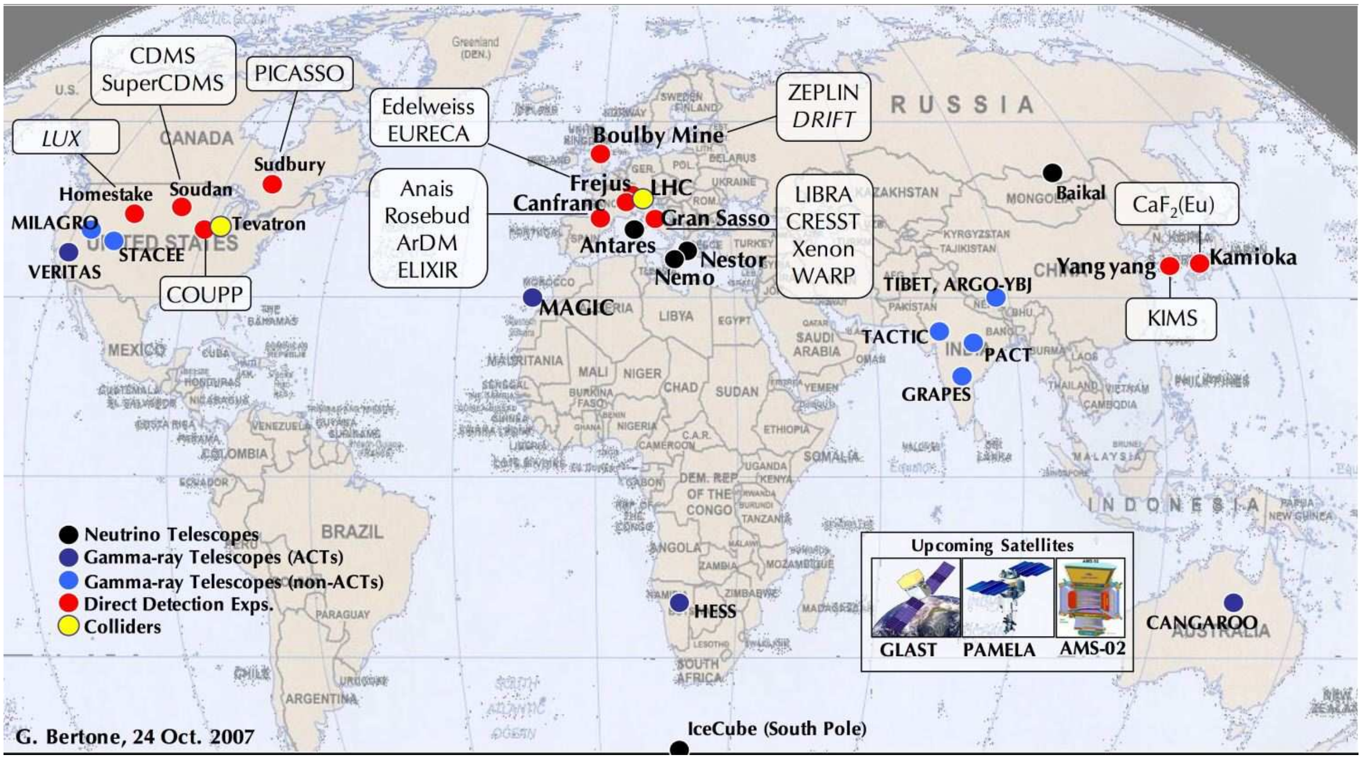

FIG. 1: 2007 census of present and upcoming Dark Matter-related experiments. Black points denote the location of high energy neutrino telescopes; Dark-blue points are for gamma-ray Air Cherenkov Telescopes, while light-blue points are for other ground-based gamma-ray observatories. Red points are for underground laboratories hosting existing and upcoming direct detection experiments. Yellow points show the location of the Fermilab's Tevatron, and the upcoming Large Hadron Collider at CERN.

width, Sneutrino limits, searches for new charged or colored particles, searches for the Higgs or new gauge bosons, flavor changing neutral currents, $b \to s\gamma$, $B_s \to \mu^+\mu^-$, anomalous magnetic moment of the muon and electroweak precision measurements.

Together, these constraints can be very powerful, often providing very tight bounds for specific models. The LHC will test numerous classes of models, searching at scales of up to several TeV. In addition to the Higgs boson(s), the LHC will be in particular sensitive to most supersymmetry scenarios, to models with TeV-scale universal extra dimensional and to little Higgs models, which are three examples of classes of models with "natural" Dark Matter candidates. (see e.g. Refs.[6, 7, 8, 9, 10, 11, 12, 13, 14]).

In order to show the potential and the inevitable limits of an accelerator-only approach, we focus on Supersymmetry (SUSY), which is the most studied, and possibly the most promising, extension of the Standard Model of particle physics. In SUSY, a discrete symmetry, known as R-parity, is often imposed in order to forbid lepton and baryon violating processes which could lead, for instance, to proton decay. As a consequence, SUSY particles are only produced or destroyed in pairs, thus making the lightest supersymmetric particle (LSP) stable. Remarkably, in large areas of the parameter space of SUSY models, the LSP is an electrically neutral particle, the lightest neutralino, $\tilde{\chi}^0_1$, which therefore constitutes a very well motivated candidate for dark matter, within the class of WIMPs. In the left panel of Fig. 3, the reach of the LHC is shown [11]. It is interesting to note that in the region of the MSSM which is the most difficult to probe at the LHC, direct dark matter detection rates are very high [16].

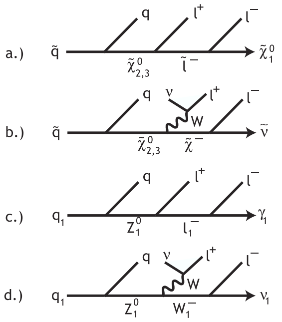

FIG. 2: Four scenarios for decay chains observed at LHC. Each exhibits jets, hard leptons, and missing energy. Distinguishing between these cases may not be possible with LHC alone. From Ref. [15]

Since we cannot observe with the LHC the final-state

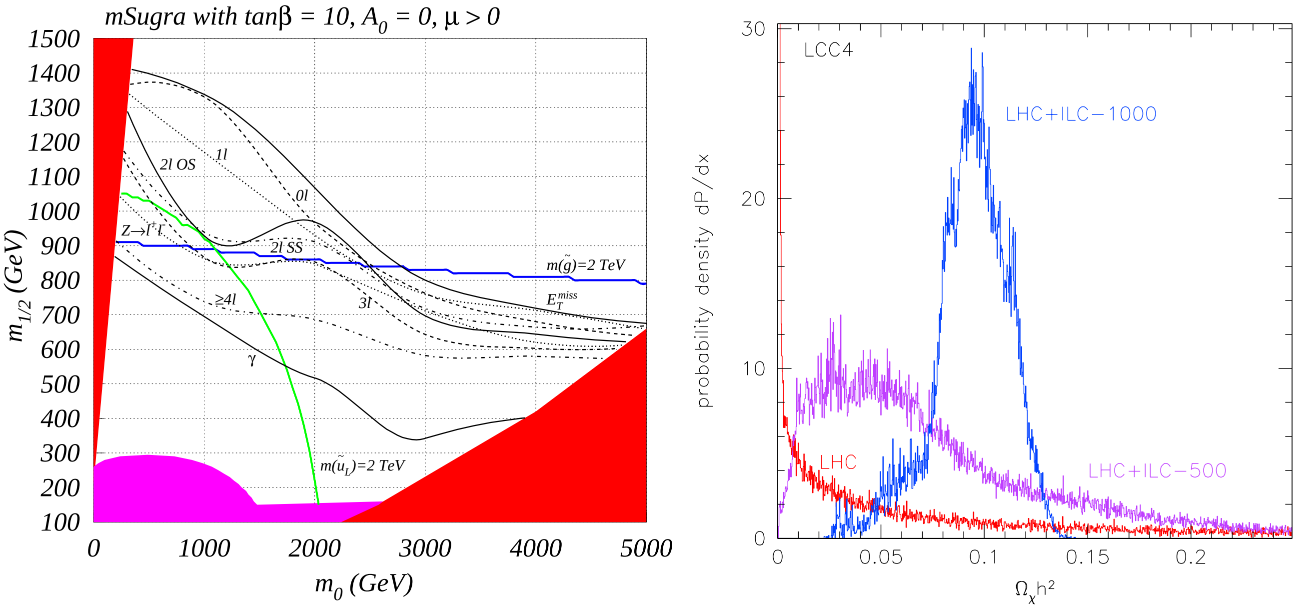

FIG. 3: *Left Panel.* The reach of the Large Hadron Collider (LHC) in the $(m_0, m_{1/2})$ plane of the mSUGRA scenario, with $\tan\beta = 10$, $A_0 = 0$ and positive μ, for a variety of channels. Also shown are the 2 TeV up squark and 2 TeV gluino mass contours. The red regions are excluded by theoretical constraints, while the magenta region is excluded experimentally. 100fb^{-1} of integrated luminosity is assumed. From Ref. [11]. *Right Panel.* Relic density measurement for one of the four benchmark points discussed in [15]. Histograms give the probability distribution for the reconstructed Ωh^2, given three different sets of accelerator constraints. Results for the LHC make use of the assumption that the underlying physics model is supersymmetry (which might not emerge clearly from the LHC data alone). The difficulty in reconstructing the relic density of a WIMP, based on LHC data only is apparent, suggesting the need of a multidisciplinary approach to DM searches. From Ref. [15]

WIMPs, we cannot learn the energies and momenta of the produced particles from the final state. Without knowing the rest frame of the massive particles, it is then very difficult to determine the spins of these particles or to specifically identify their decay modes. In Fig. 2 (taken from Ref. [15]) we show four models of the decay of a colored primary particle. Examples (a) and (b) are drawn from models of supersymmetry in which the WIMP is the supersymmetric partner of the photon or neutrino. Examples (c) and (d) are drawn from models of extra dimensions in which the WIMP is, similarly, a higher-dimensional excitation of a photon or a neutrino. The observed particles in all four decays are the same and the uncertainty in reconstructing the frame of the primary colored particle make it difficult to discriminate the subtle differences in their momentum distributions. Although model-dependent features can help distinguishing the cases of supersymmetry and extra dimensions [17, 18] it is unlikely that the LHC will unambiguously identify the nature of the WIMPs.

Even if new particles are identified, it might be difficult to understand whether they can account for *all* the DM in the Universe. In fact, it will be necessary to infer their relic density from physical quantities measured at accelerator, a process that will require some assumptions on the particle physics and cosmological setup. Even assuming, say, a minimal supersymmetric scenario and a standard expansion history of the Universe, this program may turn out to be impossible with LHC data only.

A detailed study, along these lines, has been performed by Baltz et al. [15], who have analyzed 4 benchmark points in a minimal supersymmetric scenario, showing that only a poor reconstruction of the relic density will be possible in most cases. We show in the right panel of fig. 3 the probability distribution for the DM relic density, for their benchmark point LCC4, which is chosen in a region where the A^0 resonance makes an important contribution to the neutralino annihilation cross section. In the same figure, the improvements in the determination of the relic densities with two different versions of a future Linear Collider are also shown.

This case is representative of a large portion of the theory parameter space where the reconstruction of the relic density of DM particles cannot be performed at the level of accuracy that matches existing and upcoming CMB experiments such as WMAP and Planck.

Furthermore, one has to keep in mind that unexpected surprises may await us, such as a non Standard expansions history of the Universe (in which case our relic density calculations should be revised) or a much more complicated "dark sector" in extensions of the Standard Model of particle Physics (in which case our calculations make no sense at all).

It is therefore crucial to perform all possible searches,

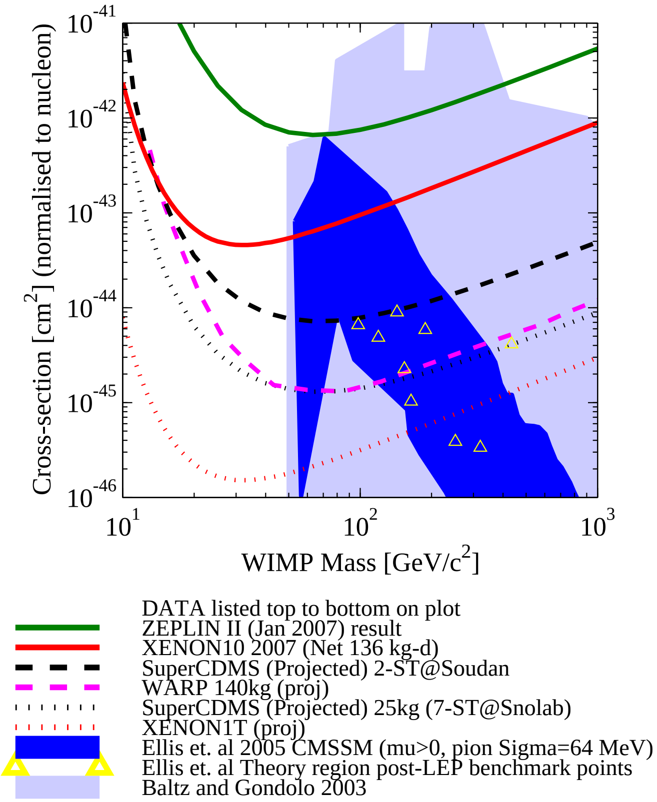

FIG. 4: Sensitivity of current and planned direct detection experiments [19].

including direct and indirect DM searches discussed below, and to devise strategies that would allow us to combine the information from a large set of diverse experiments into a consistent theoretical scenario.

III. GETTING THE MOST OUT OF DIRECT SEARCHES

DM can be searched for *directly*, as DM particles passing through the Earth interact inside large detectors. The field of direct searches is well-established, with many experiments currently operating or planned (see fig.4 for an example of the reach of present and upcoming direct detection experiments in the $\sigma_{\chi N}$–m_χ plane).

The idea is to measure the recoil energy of nuclei hit by DM particles in large detectors. The rate at which these interactions occur is typically very small, and it is approximately given by

$$R \approx \sum_i N_i n_\chi < \sigma_{i\chi} >, \qquad (1)$$

where the index, i, runs over nuclei species present in the detector, N_i is the number of target nuclei in the detector, n_χ is the local WIMP density and $< \sigma_{i\chi} >$ is the cross section for the scattering of WIMPs off nuclei of species i, averaged over the relative WIMP velocity with respect to the detector (see e.g. Ref. [20]).

Direct detection relies on scalar, or *spin-independent*, couplings, describing coherent interactions of DM with the entire nuclear mass, and on axial, or *spin-dependent*, couplings, describing the interaction of DM with the spin-content of the nucleus. Experimental efforts have so far focused on targets which enhance the scalar-interaction scattering rate, but as we shall see below, the quantification of both types of interactions, by measurement of the scattering cross-section on multiple target nuclei significantly improves our ability to identify the nature of DM particles. We recall here that spin-dependent couplings are also important for indirect DM searches, as detection of high energy neutrinos from DM annihilations at the center of the Sun, is only possible for candidates with large enough spin-dependent interactions with the nuclei of the Sun (see below for further details, and see also Ref. [21]).

Before discussing the details of direct detection, we recall that if DM exists in the form of particles, its interactions must be truly weak, for a very wide range of masses. In fact, a new and largely model-independent constraint on the dark matter scattering cross section with nucleons, which actually relies on an indirect-detection approach, was recently derived in Ref. [22]. When the dark matter capture rate in Earth is efficient, the rate of energy deposition by dark matter self-annihilation products would grossly exceed the measured heat flow of Earth. This improves the spin-independent cross section constraints by many orders of magnitude, and closes the window between astrophysical constraints (at very large cross sections) and underground detector constraints (at small cross sections). For DM masses between 1 and 10^{10} GeV, the scattering cross section of dark matter with nucleons is then bounded from above by the latter constraints, and hence must be truly weak, as usually assumed. In fig. 5 we show the regions of the $\sigma_{\chi N}$–m_χ plane where dark matter annihilations would overheat Earth, along with the astrophysical and ground-based constraints (see Ref. [22] for further details).

A natural question to ask is to what accuracy direct detection experiments can determine parameters such as the DM mass and the scattering cross-section off nucleons. Furthermore, it is important to understand how these parameters can be used to identify the underlying theoretical framework, e.g. discriminating neutralino DM from other candidates. It was recently shown that assuming a DM particle with scattering cross section of 10^7 pb, i.e. just below current exclusion limits, and fixing the local DM velocity distribution and density, an exposure of 3×10^3 ($3 \times 10^4, 3 \times 10^5$) kg day is needed in order to measure the mass of a light DM particle with an accuracy of roughly 25% (15%,2.5%) [23]. This corresponds more or less to the three proposed phases of SuperCDMS. These numbers increase with increasing WIMP mass, and for DM particles heavier than 500GeV, even with a large exposure it will only be possible to place a lower limit on

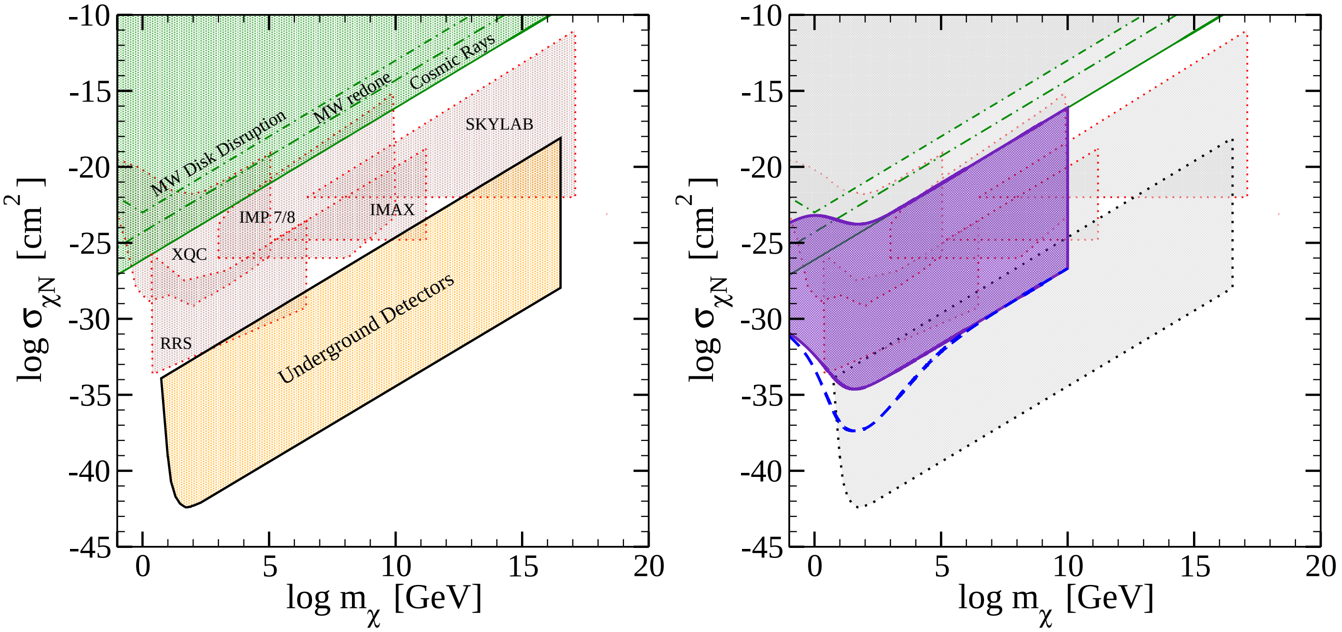

FIG. 5: *Left Panel.* Excluded regions in the $\sigma_{\chi N}$–m_χ plane. From top to bottom, these come from astrophysical constraints (dark-shaded), re-analyses of high-altitude detectors (medium-shaded), and underground direct dark matter detectors (light-shaded). *Right Panel.* Inside the heavily-shaded region, dark matter annihilations would overheat Earth. Below the top edge of this region, dark matter can drift to Earth's core in a satisfactory time. Above the bottom edge, the capture rate in Earth is nearly fully efficient, leading to a heating rate of 3260 TW (above the dashed line, capture is only efficient enough to lead to a heating rate of $\gtrsim$ 20 TW). Both figs. from Ref. [22].

the mass [23].

Recently, the need of combining spin-dependent and -independent techniques in order to effectively identify the nature of DM, has been emphasized in Ref. [24].

To be more precise, let us focus on two specific classes of DM candidates. The first one is the aforementioned neutralino, arising in supersymmetric extensions of the Standard Model of particle physics. In order to determine the theoretical predictions for the neutralino detection cross section we follow the analysis in Ref. [24] where a random scan in the effective MSSM (effMSSM) scenario, with input quantities defined at the electroweak scale [25] has been performed. The mass parameters have been taken in the range $0 \leq \mu$, m_A, M_1, A, $m \leq 2$ TeV with $3 \leq \tan\beta \leq 50$. A small non-universality in squark soft masses has also been included, taking $m^2_{Q,u,d} = (1 \ldots 5)\, m^2$. Noteworthy, regions with large $\sigma^{\rm SD}_{\tilde{\chi}^0_1 - p}$ are obtained, some of which predict a small $\sigma^{\rm SI}_{\tilde{\chi}^0_1 - p}$. A second scan was performed in the framework of supergravity-inspired models in which the soft terms are inputs at the grand unification scale. We consider the most general situation, with non-universal scalar and gaugino masses, exploring the scenarios presented in [26] for $3 \leq \tan\beta \leq 50$. Another theoretically very well motivated candidate arises in theories with Universal Extra Dimensions (UED), in which all fields are allowed to propagate in the bulk [27]. In this case, the Lightest Kaluza-Klein Particle (LKP) is a viable DM candidate, likely to be associated with the first KK excitation of the hypercharge gauge boson [28, 29], usually referred to as $B^{(1)}$. In absence of spectral degeneracies, the $B^{(1)}$ would achieve the appropriate relic density for masses in the 850–900 GeV range [28]. Interestingly, due to the quasi-degenerate nature of the KK spectrum, this range can be significantly modified, due to coannihilations with first [33, 34] and second [35, 36, 37] KK-level modes. The allowed mass range was also found to depend significantly on the mass of the Standard Model Higgs boson [35], and in general on the matching contributions to the brane-localized kinetic terms at the cut-off scale (see the discussion in Ref. [33]). The LKP models tend to populate a different region of the parameter space with respect to SUSY scenarios, because of the larger spin-dependent cross-section.

Supposing an experiment succeeds in directly detecting DM particles, it is interesting to consider how the nature of the DM (e.g. neutralino or LKP) might be determined. The possibility of combining the information from different detection targets make it possible to determine the nature of DM, upon successful detection, with much better accuracy [24]. As shown in Fig. 6(a), in fact, the measurement of an event rate in an experiment such as the Chicagoland Underground Observatory (COUPP) [40], does reduce allowed models, but does not generally place significant constraints on coupling parameters or on the nature of detected DM (i.e. neutralino or LKP).

However, as shown in Fig. 6b), subsequent detection

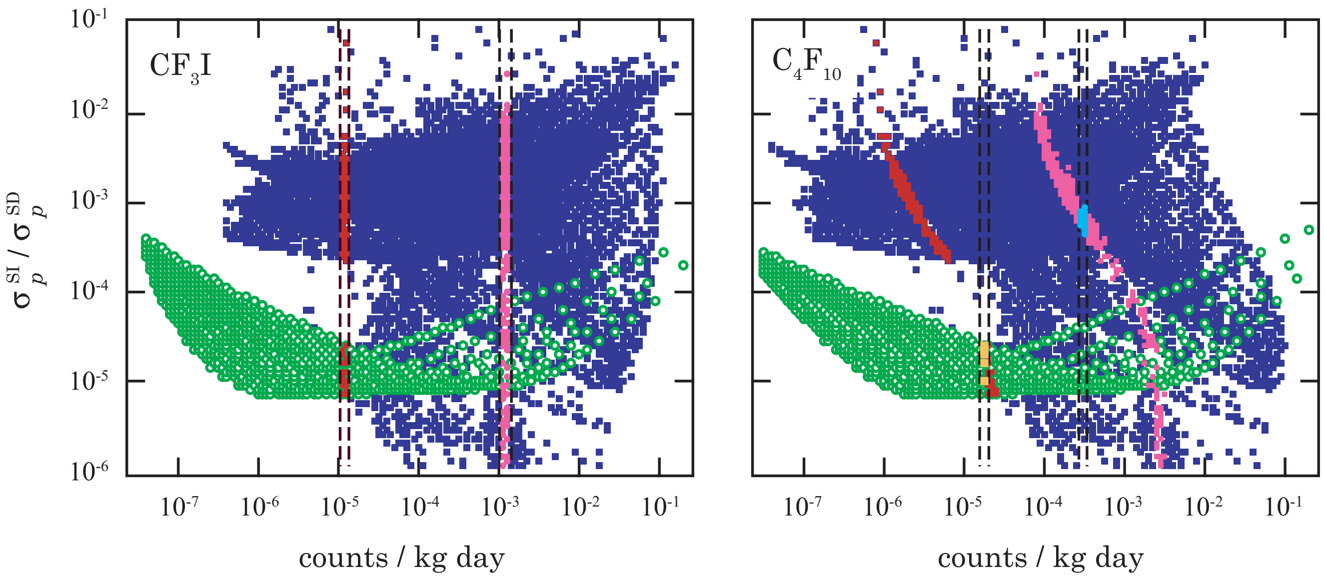

FIG. 6: *Left Panel:* The detection of a DM signal with a CF_3I detector can only loosely constrain DM candidates (blue squares for neutralinos, green circles for the LKP) in the $\sigma_p^{SI}/\sigma_p^{SD}$ versus count-rate plane. Red (magenta) dots show the many models consistent with a measurement of $\sim 10^{-5}$ (10^{-3}) counts / kg day on CF_3I. *Right Panel:* measurement of the event rate in a second detection fluid such as C_4F_{10}, with lower sensitivity to spin-independent couplings, effectively reduces the remaining number of allowed models–orange (aqua) dots–and generally allows discrimination between the neutralino and the LKP (a 10% uncertainty in the measurements is adopted here for illustration). From Ref. [24]

of an event rate on a second target does substantially reduce the allowed range of coupling parameters, and allows, in most cases, an effective discrimination between neutralino and LKP dark matter. The combination of detector fluids used in Fig. 6 is effective in reducing the allowed range of $\sigma_p^{SI}/\sigma_p^{SD}$ because massive iodine nuclei have a large SI coupling, while fluorine nuclei have a large SD_p coupling. It must be noted that fluorine and iodine have very similar neutron cross sections. Monte Carlo simulations show that CF_3I and C_3F_8 or C_4F_{10} exhibit essentially the same response to any residual neutron background, i.e., neutrons cannot mimic an observed behavior such as that described in the discussion of Fig. 6. Other combinations of targets such as germanium and silicon are more prone to systematic effects where residual neutron recoils can mimic the response expected from a WIMP with dominant spin-independent couplings.

The arguments presented in Ref. [24] can be easily generalized to a combination of data from experiments using targets maximally sensitive to different couplings, supporting the tenet that a large variety of dark matter detection methods is presently desirable.

IV. ASTROPHYSICAL DATA: FROM HINTS TO SMOKING-GUNS

The difficulty of obtaining from astrophysical observations conclusive answers on the nature of DM, is witnessed by the numerous conflicting claims of discovery, recently appeared in literature. A number of observations have been in fact "interpreted" in terms of DM, without providing, though, conclusive enough evidence to claim "discovery". The reason is simple: our understanding of the nature and distribution of DM is so poor that we have enough freedom in the choice of physical parameters, such as the DM mass and annihilation rate (roughly speaking equal to the product of the annihilation cross-section times the integral of the density squared), to fit any unexplained "bump" observed in astrophysical spectra.

Examples of possible hints of discovery recently appeared in literature include (see also the discussion in Refs. [41, 42]):

- **MeV Dark Matter.** The INTEGRAL observation of an intense 511 keV annihilation line from a region of size ≈ 10° centered around the galactic center [43] has reopened an old debate on the origin of the population of positrons observed in the Galactic bulge.

  The large uncertainties associated with the many astrophysical explanations proposed in the literature have left the door open to more "exotic" explanations. In particular, the possibility to explain the data in terms of DM annihilations immediately attracted the attention of particle astrophysicists. A simple calculation, however, suggested that any candidate with a mass above the pion mass would inevitably produce gamma-rays and synchrotron emission far above the experimental data. In particular, if the 511 keV emission was due to positrons

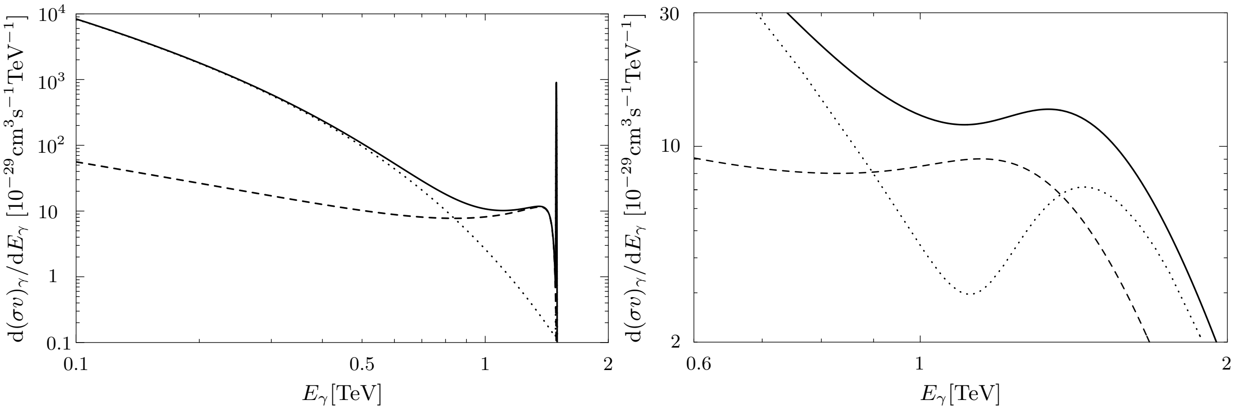

FIG. 7: *Left Panel:* The total differential photon distribution for a heavy neutralino. Also shown separately is the contribution from radiative processes $W^+W^-\gamma$ (dashed), and the W fragmentation together with the $\gamma\gamma$, $Z\gamma$ lines (dotted).*Right Panel:* Same spectra as seen by a detector with an energy resolution of 15 percent. Both figures from Ref. [72]

produced by annihilation of neutralinos, the associated gamma-ray flux would exceed the observed EGRET flux by seven orders of magnitude. A Light DM candidate was instead shown to successfully reproduce the normalization of the observed 511 keV line without violating any other observational constraint [44]. The Light DM interpretation is to be considered *tentative* until one can find a smoking-gun for it, or make a testable prediction. The first prediction, i.e. the detection of an annihilation line from a dwarf galaxy, has so far failed [45] , while further analyses have progressively reduced the allowed parameter space of DM particles. On one side, an upper limit on the mass comes from the analysis of Internal Bremsstrahlung emission (≈ 20 MeV, see Ref. [46]) and in-flight annihilation (of order $3-7$ MeV, see Refs. [47, 48]). On the other side, an analysis based on the explosion of the supernova SN1987A sets a lower limit of ≈ 10 MeV, thus apparently ruling out Light DM as a viable explanation of the 511 keV line [49], at least in its most simple realization. Recently, these constraints have been challenged, and the claim has been made that it is still possible to accommodate all existing constraints while still providing a satisfactory explanation of the INTEGRAL data [50]: the debate is thus still open. Peculiar spectral features such as a 2γ line [51]), or discovery in collider searches would allow to promote the Light DM scenario from "tentative interpretation" to "discovery".

- **The GeV Excess** Evidence for WIMPs with a mass of tens of GeV, producing through their annihilation a "bump" in the Galactic gamma-ray emission observed by EGRET was recently claimed in Ref. [52]. Although in principle very exciting, the emission is characterized by a distribution which is very different from the one naïvely predicted by numerical simulations (more intense towards the galactic center), being in the shape of a ring around the galactic center. This is not sufficient of course to rule out this scenario, but there are still numerous difficulties associated with this intepretation, that have been recently highlighted in Ref. [53], in particular regarding the required ring-shaped distribution of DM, as well as the apparent incompatibility with anti-proton measurements. As in the case of MeV DM, this doesn't mean that the proposed interpretation is wrong, but simply that a different approach is needed to obtain conclusive evidence.

- **The Galactic center.** The discovery of a gamma-ray source in the direction of Sgr A* has long been considered a potentially perfect signature of the existence of particle DM, as thoroughly discussed in Refs. [54, 55, 56, 57, 58, 59, 60]. However, the gamma-ray source observed by EGRET at the Galactic center might be slightly offset with respect to the position of Sgr A*, a circumstance clearly at odds with a DM interpretation [61].

  Recently the gamma-ray telescope HESS has detected a high energy source, spatially coincident within $1'$ with Sgr A* [62] and with a spectrum extending above 20 TeV. Although the spatial coincidence is much more satisfactory than in the case of the EGRET source, the "exotic" origin of the signal is hard to defend, since the implied mass scale of the DM particle (well above 20 TeV, to be consistent with the observed spectrum) appears to be difficult to reconcile with the properties of commonly studied candidates , and the fact that the spectrum is a power-law, then, points towards a standard astrophysical source (see e.g. the discussion Ref. [63]). The galactic center, however, remains an interesting target for GLAST, since it will explore a range of energies below the relatively high threshold of HESS, where a DM signal could be hiding [64]. The recent claim that the profile

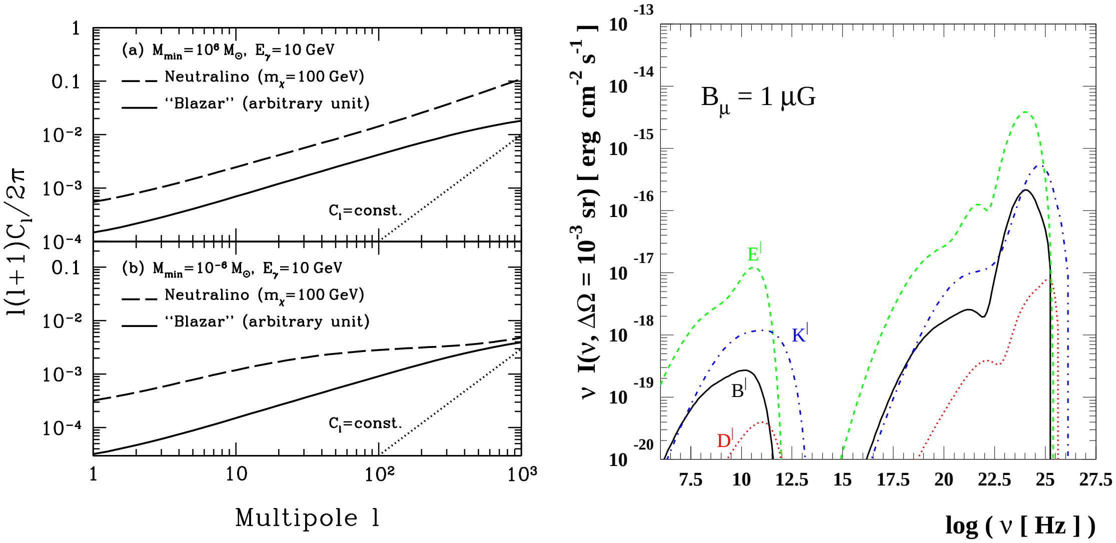

FIG. 8: *Left Panel:* Shape of the angular power spectrum of the CGB expected from unresolved blazar-like sources (solid lines) with arbitrary normalizations. The power spectrum from annihilation of neutralinos with $m_\chi = 100$ GeV is also plotted as the dashed lines. The adopted gamma-ray energy is 10 GeV, and the minimum mass of dark matter halo is (a) $10^6 M_\odot$, and (b) $10^{-6} M_\odot$. The dotted lines show the shot noise (C_l = const.) with arbitrary normalizations, which represent the power spectrum of very rare sources. From Ref. [81]. *Left Panel:*Multi-wavelength spectra for four different benchmark DM models, for a best fit NFW profile, and a mean magnetic field equal to $1\mu G$. From Ref. [88], see *ibid.* for more details.

of large galaxies could be much more shallow than previously thought [65], should not discourage further studies, especially in view of the possible enhancement of the DM density due to interactions with the stellar cusp observed at the Galactic center [66].

- **WMAP Haze.** Aside from the expected astrophysical foregrounds, the WMAP observations have revealed an excess of microwave emission in the inner 20° around the center of the Milky Way. This origin of this WMAP "Haze" is unknown, and conventional astrophysical explanations such as thermal Bremsstrahlung from hot gas, thermal or spinning dust, and Galactic synchrotron appear to be unlikely. Dark matter annihilations have been suggested as a possible explanation [67, 68], and if this is the case, GLAST may find an associated gamma-ray signal [69].

Despite the difficulties associated with most of these strategies, and despite the lack of conclusive evidence, all these claims should be taken seriously and further investigated without prejudice, especially in view of the fact that we don't know what DM is. At the same time, it is important to look for clear smoking-gun of DM annihilation, and study theoretical scenarios with unambiguous signatures that can be tested with present and future experiments. To this aim, we summarize here some recently proposed ideas that go precisely in this direction, and that may shed new light on the nature of particle DM.

a. **Spectral Features.** The first, and more clear signature that one may hope to detect is to identify distinctive spectral features in the DM annihilation spectra.

It might be possible for instance to detect annihilation lines at an energy equal to the DM particle mass. In the case of SUSY, although there are no tree level processes for neutralino annihilation into photons, loop level processes to $\gamma\gamma$ and γZ^0 are very interesting, and may provide a spectral line feature observable in indirect detection experiments [70, 71]. Similar calculations have been performed for other candidates such as the aforementioned $B^{(1)}$ in theories with Universal Extra Dimensions [72], and the so-called Inert Higgs DM [73].

Aside from the rather featureless gamma-ray spectrum produced by the fragmentation of gauge bosons and quarks, there are additional, more distinctive, sources of photons. Internal Bremsstrahlung of W pair final states at energies near the mass of the neutralino appears particularly promising. For masses larger than about 1 TeV it results in a characteristic signal that may dominate not only over the continuous spectrum from W fragmentation, but also over the $\gamma-\gamma$ and $\gamma-Z$ line signals [74]. In figure 7 we show the importance of radiative corrections $W^+W^-\gamma$ for the case of a heavy neutralino, as compared with line signals. Also shown are the same spectra convolved with the energy resolution of a GLAST-like detector.

Recently, Bringmann et al. [75] have computed elec-

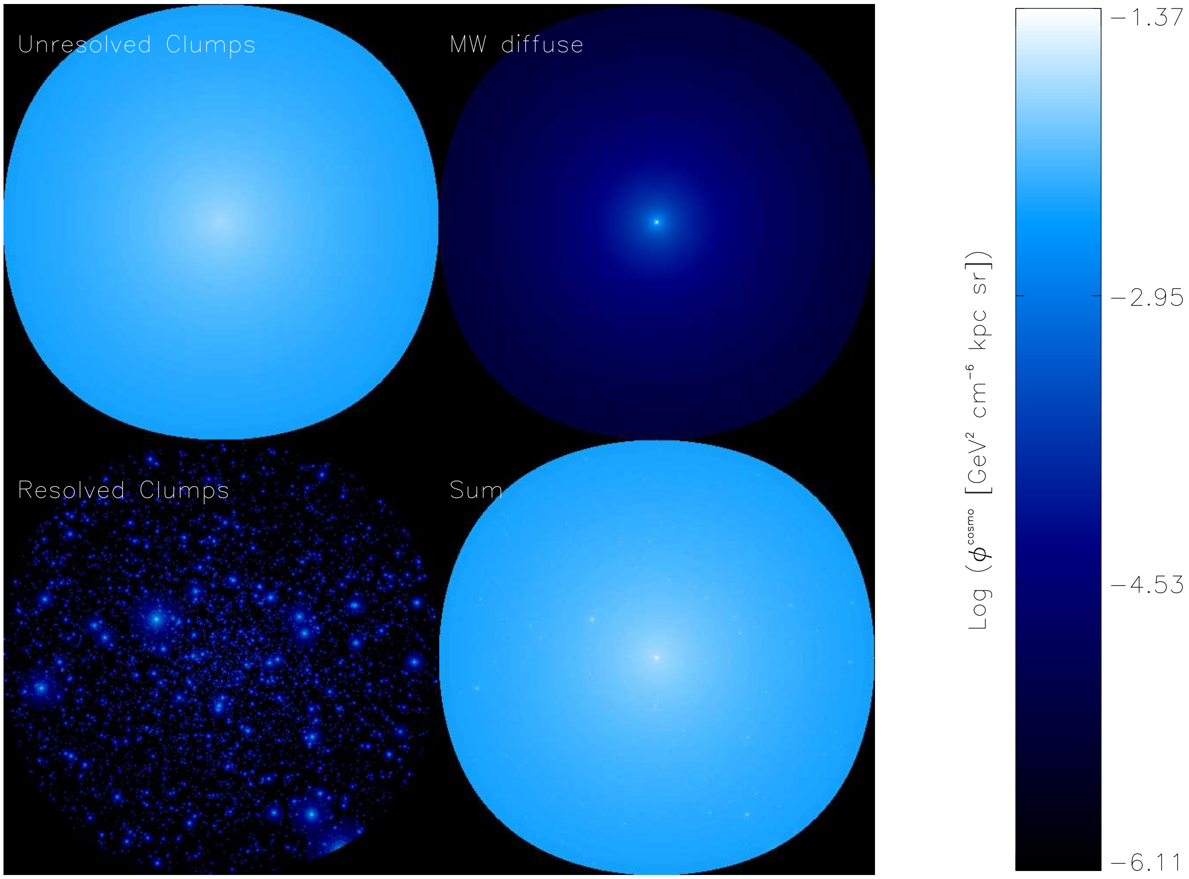

FIG. 9: Map of $\Phi^{\rm cosmo}$ (proportional to the annihilation signal) for the Bullock et al. model, in a cone of 50° around the Galactic Center, as seen from the position of the Sun. Upper left: smooth subhalo contribution from unresolved halos. Upper right: MW smooth contribution. Lower left: contribution from resolved halos. Lower right: sum of the three contributions. From Ref. [93].

tromagnetic radiative corrections to all leading annihilation processes in the MSSM and mSUGRA, and pointed out that in regions of parameter space where there is a near degeneracy between the dark matter neutralino and the tau sleptons, radiative corrections may boost the gamma-ray yield by up to three or four orders of magnitude. This turns out to be true even for neutralino masses considerably below the TeV scale, and leads to a sharp step at an energy equal to the mass of the dark matter particle. For a considerable part of the parameter space, internal Bremsstrahlung appears then more important for indirect dark matter searches than line signals [75].

The possibility to discriminate an annihilation signal from ordinary astrophysical sources has been addressed in Refs. [76, 77]. If DM annihilation signals are within the reach of GLAST, the observation of the high-energy cut-off would allow a measurement of the DM particle mass with an accuracy equal to the energy resolution of the experiment, i.e. $\Delta E/E \approx 10\%$ [77].

b. **Gamma-ray background.** The first calculation of the gamma-ray background produced by the annihilations of DM in all structures, at any redshift, was performed in Ref. [78] , and then further studied in Refs. [79, 80]. The annihilation background can be expressed as

$$\Phi(E) = \frac{\Omega_{DM}^2 \rho_c^2}{8\pi H_0} \frac{\sigma v}{m_\chi^2} \int_0^{z_{max}} \mathrm{d}z \frac{\Delta^2}{h(z)} N(E') \qquad (2)$$

where $N(E')$ is the gamma-ray spectrum per annihilation, H_0 is the Hubble parameter, $E' = E(1+z)$ and $h(z) = [(1+z)^3 \Omega_{DM} + \Omega_\Lambda]^{1/2}$. The information on the shape of individual DM halos in encoded in Δ^2, which is essentially the integral of ρ^2 over the virial volume of the halo. Although it is unlikely that the annihilation background will be detected without first detecting a prominent gamma-ray source at the Galactic center [82], the characteristic power spectrum of the gamma-ray background would discriminate its DM origin from ordinary astrophysical sources [81].

We show in the left panel of fig. 8 the power spectrum of the gamma-ray background produced by annihilation of neutralinos with $m_\chi = 100$ GeV, compared with the one relative to unresolved blazar-like sources. Above $l \sim 200$ the DM spectrum continues to grow whereas the blazar spectrum flattens out, due to the cut-off adopted by the authors corresponding to the minimum mass of halos hosting blazars ($\approx 10^{11} M_\odot$). The annihilation spectrum thus appear to have much more power at large angular scales, which should be easily distinguished from the blazar spectrum.

There are large uncertainties associated with this calculation, mainly due to our ignorance of the DM profile in the innermost regions of halos, and of the amount of substructures. The existence of mini-spikes (see below) would also dramatically affect the predicted result [83]. But the clear prediction is made that if the observed background has the peculiar shape discussed above, this may be consider as a hint of DM annihilations. Recently the calculation of the *neutrino* background from DM annihilations has been performed, adopting a formalism very similar to the one sketched above. The comparison with observational data allows to set an interesting, and very general, upper bound on the dark matter total annihilation cross section [84].

c. **Multi-messenger approach.** An alternative strategy is to employ a multi-messenger, multi-wavelength approach. In fact, despite the freedom in the choice of DM parameters makes the interpretation of observational data rather inconclusive, one can always combine the information at different wavelengths, and with different messengers, to obtain more stringent constraints. In fact, gamma-rays are typically (but not exclusively) produced through annihilation and decay chain involving neutral pions

$$\chi\overline{\chi} \rightarrow q\overline{q} \rightarrow [\text{fragmentation}] \rightarrow \pi^0 \rightarrow 2\gamma \tag{3}$$

Every time gamma-rays are produced this way, leptons and neutrinos are also produced following the chain

$$\chi\overline{\chi} \rightarrow q\overline{q} \rightarrow [\text{fragmentation}] \rightarrow \pi^\pm \rightarrow l, \nu_l, ... \tag{4}$$

An example of this approach is the combined study of the gamma-ray emission from the Galactic center and the associated synchrotron emission produced by the propagation of electron-positron pairs in the Galactic magnetic field [32, 58, 85, 86]. Similarly one can investigate what the flux of neutrinos would be, once the gamma-ray flux has been normalized to the EGRET data [87].

One can also ask what the fate of the electron-positron pairs produced by DM annihilation is in dwarf galaxies and clusters of galaxies. An example of this approach can be found in Refs. [88, 89], where the authors study the synchrotron and gamma-ray emission from Draco and from the Coma cluster. In the right panel of fig. 8 we show the multi-wavelength spectra of Draco, relative to four different DM benchmark models, assuming a NFW profile and a mean magnetic field of $1\mu G$.

A word of caution is in order, however, when combining information relative to different wavelengths. In fact, not only the available data, due to the different angular resolution of experiments, are relative to different physical regions, but the calculation of the associated spectra at different energies usually requires further inputs, thus introducing new parameters to the problem. The aforementioned calculation of the synchrotron emission is a typical example: although for every specific DM model the number of electron-positron pairs produced per annihilation is fixed, the calculation of the synchrotron emission requires an estimate of the diffusion of positrons and it further depends on the magnetic field profile, typically poorly constrained on the scales of interest.

d. **Clumps.** The detectability of individual DM substructures, or clumps, has been widely discussed in literature, often with contradictory results. The number of detectable clumps with a GLAST-like experiment, at 5σ in 1 year and for a WIMP DM particle in fact ranges from $\lesssim 1$ [90] to more than 50 [76] for large mass halos, while for microhalos (i.e. clumps with a mass as small as $10^{-6}\text{M}_\odot$) the predictions range from no detectable objects [91] to a large number of detectable objects, with a fraction of them exhibiting a large proper motion [92]. The apparent inconsistency of the results published so far, is actually due to the different assumptions that different groups adopt for the physical quantities that regulate the number and the annihilation brightness of DM clumps.

In particular, even in the context of the benchmark density profile introduced by Navarro, Frenk and White 1996 [NFW], the results crucially depend on the substructures mass function, their distribution within the halo host and their virial concentration $c(M, z)$ which is a function of mass and of collapse redshift of DM clumps.

It was recently shown in Ref. [93], that scenarios leading to a high number of detectable sources, as well as scenarios where micro-clumps (i.e. clumps with mass as small as $10^{-6}\text{M}_\odot$) can be detected, are severely constrained by the diffuse gamma-ray background detected by EGRET. For a fiducial DM candidate with mass $m_\chi = 100$ GeV and annihilation cross section $\sigma v = 10^{-26}$ $\text{cm}^3\ \text{s}^{-1}$, at most a handful of large mass substructures, and no micro-clumps, can be detected (at 5σ, with a 1-year exposure time, by a GLAST-like experiment) in the most optimistic scenario. We show in fig. 9 a map of a quantity defined in Ref. [93], which is proportional to the annihilation signal for a specific case (Bullock et al. concentration model), in a cone of 50° around the Galactic Center, as seen from the position of the Sun. The three contributions discussed in the paper are shown: a smooth one from unresolved subhalos; the MW smooth halo; and resolved individual halos. The sum of the three contributions is shown in the lower right panel.

e. **Mini-Spikes.** Black Holes (BHs) can be broadly divided in 3 different classes. The first class include BHs with mass smaller than ≈ 100 solar masses, typically remnants of the collapse of massive stars (recent simulations suggest that the upper limit on the mass of these objects is as low as $\approx 20 M_\odot$ [94]). There is robust evidence for the existence of these objects, coming from the observation of binary objects with compact objects whose mass exceeds the critical mass of Neutron Stars. For a review of the topic and the discussion of the pos-

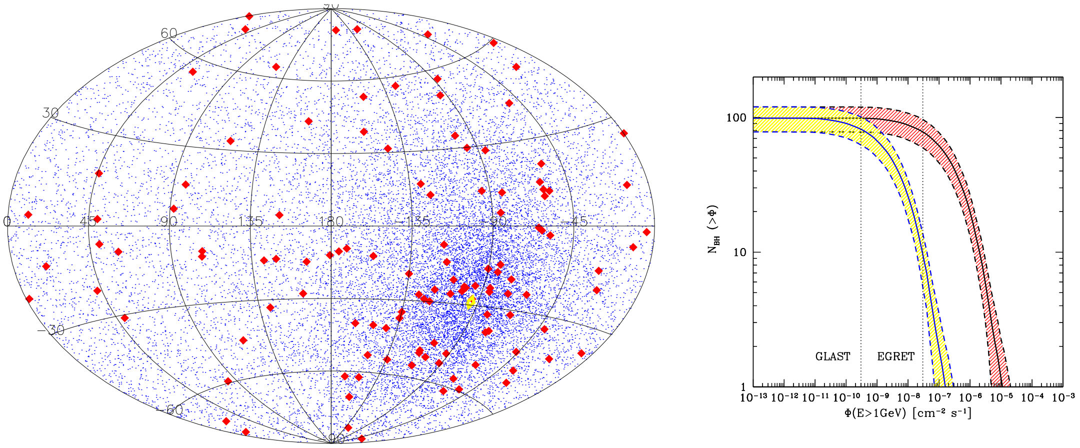

FIG. 10: *Left Panel:* Sky map in equatorial coordinates showing the position of Intermediate Mass Black Holes in one random realization of a Milky-Way like halo (red diamonds), and in all 200 realizations (blue dots). The concentration at negative declinations corresponds to the position of the Galactic center (black open diamond). From Ref. [112]. *Right Panel:* IMBHs integrated luminosity function, (number of mini-spikes detectable with an experiment of sensitivity ϕ) for IMBHs with mass $\sim 10^5 M_\odot$. The upper (lower) line corresponds to $m_\chi = 100$ GeV, $\sigma v = 3 \times 10^{-26}$ cm^3 s^{-1} ($m_\chi = 1$ TeV, $\sigma v = 10^{-29}$ cm^3 s^{-1}). For each curve we also show the 1-σ scatter among different realizations of Milky Way-sized host DM halos. We show for comparison the 5σ point source sensitivity above 1 GeV of EGRET and GLAST (1 year). From Ref. [106].

sible smoking-gun for Stellar Mass BHs see e.g. [95] and references therein.

The existence of Supermassive BHs (SMBHs) , lying at the center of galaxies (including our own), is also well-established (see e.g. Ref. [96]), and intriguing correlations are observed between the BHs mass and the properties of their host galaxies and halos [97, 98, 99, 100, 101, 111]. From a theoretical point of view, a population of massive seed black holes could help to explain the origin of SMBHs. In fact, observations of quasars at redshift $z \approx 6$ in the Sloan Digital survey [102, 103, 104] suggest that SMBHs were already in place when the Universe was only ~ 1 Gyr old, a circumstance that can be understood in terms of rapid growth starting from "massive" seeds (see e.g. Ref. [105]).

This leads us to the third category of BHs, characterized by their *intermediate* mass. In fact, scenarios that seek to explain the properties of the observed supermassive black holes population result in the prediction of a large population of wandering Intermediate Mass BHs (IMBHs). Here, following Ref. [106], we consider two different formation scenarios for IMBHs. In the first scenario, IMBHs form in rare, overdense regions at high redshift, $z \sim 20$, as remnants of Population III stars, and have a characteristic mass-scale of a few $10^2 M_\odot$ [107] (a similar scenario was investigated in Ref. [108, 109, 110]). In this scenario, these black holes serve as the seeds for the growth supermassive black holes found in galactic spheroids [96]. In the second scenario, IMBHs form directly out of cold gas in early-forming halos and and are typified by a larger mass scale, of order $10^5 M_\odot$ [111]. In the left panel of Fig. 10 we show the distribution of IMBHs in the latter scenario, as obtained in Ref. [112].

The effect of the formation of a central object on the surrounding distribution of matter has been investigated in Refs. [118, 119, 120, 121] and for the first time in the framework of DM annihilations in Ref. [122]. It was shown that the *adiabatic* growth of a massive object at the center of a power-law distribution of DM with index γ, induces a redistribution of matter into a new power-law (dubbed "spike") with index $\gamma_{sp} = (9-2\gamma)/(4-\gamma)$ This formula is valid over a region of size $R_s \approx 0.2 r_{BH}$, where r_{BH} is the radius of gravitational influence of the black hole, defined implicitly as $M(< r_{BH}) = M_{BH}$, with $M(< r)$ mass of the DM distribution within a sphere of radius r, and M_{BH} mass of the Black Hole [123]. The process adiabatic growth is in particular valid for the SMBH at the Galactic center. A critical assessment of the formation *and survival* of the central spike, over cosmological timescales, is presented in Refs. [124, 125] (see also references therein). The impact of the spike growth and subsequent destruction on the gamma-ray background produced by DM annihilations has been studied in Ref. [126].

Here we will not further discuss the spike at the Galactic center, and will rather focus our attention on *mini-spikes* around IMBHs. If $N_\gamma(E)$ is the spectrum of gamma-rays per annihilation, the gamma-ray flux from an individual mini-spike can be expressed as [106]

$$\Phi_\gamma(E) = \phi_0 m_{\chi,100}^{-2} (\sigma v)_{26} D_{\rm kpc}^{-2} L_{\rm sp} N_\gamma(E) \tag{5}$$

with $\phi_0 = 9 \times 10^{-10} \mathrm{cm}^{-2}\mathrm{s}^{-1}$. The first two factors depend on the particle physics parameters, viz. the mass of the DM particle in units of 100 GeV $m_{\chi,100}$, and its annihilation cross section in units of $10^{-26}\mathrm{cm}^3/\mathrm{s}$, $(\sigma v)_{26}$, while the third factor accounts for the flux dilution with the square of the IMBH distance to the Earth in kpc, $D_{\rm kpc}$. Finally, the normalization of the flux is fixed by an adimensional *luminosity factor* $L_{\rm sp}$, that depends on the specific properties of individual spikes. In the case where the DM profile *before* the formation of the IMBH follows the commonly adopted Navarro, Frenk and White profile [127], the final DM density $\rho(r)$ around the IMBH will be described by a power law $r^{-7/3}$ in a region of size R_s around the IMBHs. Annihilations themselves will set an upper limit to the DM density $\rho_{\rm max} \approx m_\chi/[(\sigma v)t]$, where t is the time elapsed since the formation of the mini-spike, and we denote with $R_{\rm c}$ the "cut" radius where $\rho(R_{\rm c}) = \rho_{\rm max}$. With these definitions, the intrinsic luminosity factor in Eq. 5 reads

$$L_{\rm sp} \equiv \rho^2_{100}(R_{\rm s}) R^{14/3}_{\rm s,pc} R^{-5/3}_{\rm c,mpc} \tag{6}$$

where $R_{\rm s,pc}$ and $R_{\rm c,mpc}$ denote respectively $R_{\rm s}$ in parsecs and $R_{\rm c}$ in units of 10^{-3}pc, $\rho_{100}(r)$ is the density in units of 100GeV cm^{-3}. Typical values of $L_{\rm sp}$ lie in the range $0.1 - 10$ [106].

In the left panel of Fig. 10, we show the (average) integrated luminosity function of IMBHs in scenario B. We define the integrated luminosity function as the number of black holes producing a gamma-ray flux larger than Φ, as a function of Φ. Loosely speaking, this can be understood as he number of mini-spikes that can be detected with an experiment with point source sensitivity Φ above 1 GeV. The upper (lower) line corresponds to $m_\chi = 100$ GeV, $\sigma v = 3 \times 10^{-26}$ cm^{3}s^{-1} ($m_\chi = 1$ TeV, $\sigma v = 10^{-29}$ cm^{3}s^{-1}). We show for comparison the point source sensitivity above 1 GeV for EGRET and GLAST, corresponding roughly to the flux for a 5σ detection of a high-latitude point-source in an observation time of 1 year [128]. The dashed region corresponds to the 1σ scatter between different realizations of Milky Way-sized halos. This band includes the variation in spatial distributions of IMBHs from one halo to the next as well as the variation in the individual properties of each IMBH in each realization.

The implications of the mini-spikes scenario have been investigated by several authors. Their impact on the gamma-ray background has been studied in Ref. [83], while the implications for anti-matter fluxes have been derived in Ref. [130]. A population of IMBHs similar to the one derived for the Milky Way should also be present in other spiral galaxies similar to our own; the prospects for detecting IMBHs in M31, i.e. the Andromeda Galaxy, have been studied in [131].

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