Dark Matter in $\gamma$ lines: Galactic Center vs. dwarf galaxies

Valentin Lefranc, a Emmanuel Moulin, a Paolo Panci, b Filippo Sala, c and Joseph Silk b,d,e

aDRF/Irfu, Service de Physique des Particules, CEA Saclay, F-91191 Gif-Sur-Yvette Cedex, France
bInstitut d’Astrophysique de Paris, UMR 7095 CNRS, Université Pierre et Marie Curie, 98 bis Boulevard Arago, Paris 75014, France
cLPTHE, UMR 7589 CNRS, 4 Place Jussieu, F-75252, Paris, France
dThe Johns Hopkins University, Department of Physics and Astronomy, 3400 N. Charles Street, Baltimore, Maryland 21218, U.S.A.
eBeecroft Institute of Particle Astrophysics and Cosmology, Department of Physics, University of Oxford, 1 Keble Road, Oxford OX1 3RH, U.K.

E-mail: valentin.lefranc@cea.fr, emmanuel.moulin@cea.fr, panci@iap.fr, fsala@lpthe.jussieu.fr, silk@iap.fr

Received August 13, 2016
Accepted September 15, 2016
Published September 26, 2016

Abstract. We provide CTA sensitivities to Dark Matter (DM) annihilation in $\gamma$-ray lines, from the observation of the Galactic Center (GC) as well as, for the first time, of dwarf Spheroidal galaxies (dSphs). We compare the GC reach with that of dSphs as a function of a putative core radius of the DM distribution, which is itself poorly known. We find that the currently best dSph candidates constitute a more promising target than the GC, for core radii of one to a few kpc. We use the most recent instrument response functions and background estimations by CTA, on top of which we add the diffuse photon component. Our analysis is of particular interest for TeV-scale electroweak multiplets as DM candidates, such as the supersymmetric Wino and the Minimal Dark Matter fiveplet, whose predictions we compare with our projected sensitivities.

Keywords: dark matter theory, dark matter experiments, gamma ray experiments

ArXiv ePrint: 1608.00786
Contents

1 Motivation
2 Electroweak multiplets as DM candidates 2
  2.1 Phenomenological status 3
  2.2 Sommerfeld-enhanced cross sections 3
3 Gamma ray lines searches  4
  3.1 Lines accompanied by a continuum 4
  3.2 Fluxes at Earth 5
  3.3 Galactic Center 7
  3.4 Dwarf spheroidal galaxies 8
4 CTA sensitivities  9
  4.1 DM signals and irreducible backgrounds 10
  4.2 Analysis methodology and likelihood 11
5 Results and discussion  12
6 Summary and conclusions  16

1 Motivation

By revealing the existence of the Higgs boson, the Large Hadron Collider (LHC) has now completed the Standard Model of particle physics (SM). However, the LHC has not found clear signs of new physics (NP), casting doubts on the so-called naturalness of the electroweak (EW) scale, which is arguably the strongest theoretical argument to expect new physics to exist in that range. Still, the simple assumption of Dark Matter (DM) being a weakly interacting massive particle (WIMP) motivates NP close to the electroweak scale, independently of naturalness arguments, thanks to the theoretically attractive requirement of obtaining the correct relic DM abundance via thermal freeze-out. The quest for such DM candidates is then a crucial motivation of the present experimental exploration at the energy and astroparticle frontiers.

The hitherto empty-handed experimental searches (at colliders and in direct and indirect detection) for such WIMPs are now pushing, quite generically, the mass of this kind of DM to the TeV scale. Such large masses pose a challenge to collider experiments, because of the corresponding center-of-mass energy needed to produce DM, as well as to direct detection experiments, because of the lower number density of DM particles that correspond to larger DM masses. The weak DM interactions further undermine the sensitivity of both experiments to its signals.

Indirect detection experiments are thus essential in order to probe these regimes. In their regard, lower DM particle densities imply dimmer cosmic rays fluxes originating from DM annihilations. This motivates the quest for spectral features, like lines, in the cosmic rays (CR) spectra, since they are readily distinguishable from astrophysical backgrounds even if their fluxes are moderate. Moreover, higher DM masses imply that the corresponding CR
fluxes are expected at higher energies, where the sensitivity of some telescopes — typically satellites, such as PAMELA, AMS-02 and Fermi — is limited by their size. This favours telescopes with a large effective area, most notably ground-based Cherenkov arrays, and puts them in an excellent situation to explore the WIMP Dark Matter paradigm. Cherenkov telescopes measure high-energy (up to \( \sim 100 \) TeV) cosmic \( \gamma \)-rays from specific sky regions. Currently H.E.S.S. [1], MAGIC [2] and VERITAS [3] are operating, and the next-generation Cherenkov Telescope Array (CTA) [4] is expected to start taking data towards the end of this decade.

From the point of view of particle physics, the DM annihilation in \( \gamma \)-rays is generically loop-suppressed with respect to annihilations into other cosmic rays. However, the so-called Sommerfeld effect partially compensates this hierarchy, for WIMPs with masses sufficiently larger than the mediators of their interactions with the SM. This renders \( \gamma \)-ray lines one of the most promising probes, a prominent example being that of multi-TeV scale WIMPs whose interactions are mediated by the SM EW gauge bosons.

From a more astrophysical point of view, the fact that the DM annihilation signals scale as \( \rho_{\text{DM}}^2 \) makes it interesting to explore regions where the DM density profile \( \rho_{\text{DM}} \) is enhanced, like the Galactic Center (GC) and dwarf Spheroidal galaxies (dSphs). The first has already been widely observed in the quest for lines [5–7], and has allowed placing stringent constraints on WIMP models, despite the large baryonic content and the poor knowledge of \( \rho_{\text{DM}} \) in the inner galactic regions. DSphs are much cleaner from baryons, being the most DM dominated objects known, but only Segue-I has so far been searched for \( \gamma \) lines [8]. The high rate at which new dSphs are being discovered, with excellent prospects for indirect detection, further encourages their exploration in terms of high energy \( \gamma \)-ray lines.

In this paper, motivated by the above considerations, we study the sensitivity of CTA to \( \gamma \) lines from both the GC and dSphs. We provide the expected reach in DM annihilation cross-sections into \( \gamma \gamma \), and we also compare our predictions with some prototypical WIMP models (fermion multiplets of the SM gauge group SU(2)_L) as benchmark targets. We discuss the interplay of the GC and dSph reaches, in light of the radius of the possible core of the DM distribution in the Milky Way (MW) halo.

The exposition is organised as follows: in section 2 we review EW multiplets and their phenomenology, including the Sommerfeld enhancement; in section 3 we discuss the signals that we look for, in terms both of their spectral features and of the observation targets (the GC and dSphs); in section 4 we describe the derivation of the CTA projected sensitivities to \( \gamma \)-ray lines; in section 5 we present our results; in section 6 we conclude.

## 2 Electroweak multiplets as DM candidates

Multiplets of the SM gauge group SU(2)_L are, by definition, the prototype of WIMP DM, and therefore constitute a motivated and economical benchmark for phenomenological studies. Besides being simple benchmarks, fermion SU(2)_L multiplets with zero hypercharge arise as DM candidates in motivated NP constructions. We focus here on the cases of a Majorana triplet (also known as “Wino”) and fiveplet as particularly motivated examples:

- A **Wino** is predicted to be the lightest supersymmetric particle (LSP), and therefore a candidate of DM, in models of anomaly mediation [9]. It is further motivated in models of Supersymmetry with heavy scalars [10], from the first split-SUSY proposals [11, 12] up to more recent constructions inspired by the anthropic principle (see [13] and
Irrespective of Supersymmetry, an EW fermion triplet marries minimality with other virtues, see e.g. the discussion in [14].

- The MDM 5plet emerges as the only [15, 16] viable DM candidate in the Minimal Dark Matter (MDM) framework [17, 18], where the SM is enlarged by only one particle, demanded to be (accidentally) stable thanks to gauge invariance.

### 2.1 Phenomenological status

The phenomenology of such candidates is controlled by only one free parameter, $M_{DM}$, which is fixed to 2.9 TeV (triplet) [19] and 9.4 TeV (fiveplet) [20] if the thermal freeze-out requirement is imposed. The neutral component of the multiplet is the DM, and its coannihilations with the other components in the early universe effectively increase its annihilation cross-section, and consequently the mass for which the measured relic abundance is achieved, with the respect to the naive WIMP picture. These masses are further pushed into the multi-TeV range by the Sommerfeld enhancement of the annihilation cross-section [21]. In the rest of this discussion, we will leave $M_{DM}$ as a free parameter: on the one hand, this provides a good quantification of the experimental reach, on the other hand, DM production could well be non-thermal, so that the DM mass could either be lighter (see e.g. [22]) or heavier (see e.g. [23]) than the aforementioned thermal values.

Coming now to experimental probes of these candidates, the LHC currently excludes masses lighter than $\sim 270$ GeV [24, 25], and TeV masses are not expected to be reached before construction of a 100 TeV collider, which has the potential to probe a thermal Wino [14, 26], and a fiveplet with a mass of $\sim 5$ TeV [27]. Concerning direct detection, the spin-independent cross-section with nuclei of these candidates is accidentally suppressed [28], so that TeV masses are out of reach at current and near future experiments, up to XENON-1T [29]. The TeV territory will be explored by LZ, and the thermal masses are expected to be probed only with multi-ton future detectors, such as DARWIN [30]. Concerning indirect detection, $\gamma$-rays from the GC (as first emphasised in [31, 32] for lines) and dSph are, at present, the most promising probes [20, 33]. Indeed, H.E.S.S. observations of $\gamma$-ray lines from the GC [5] already exclude both thermal benchmarks, if a profile like Einasto or NFW is assumed. For more cored profiles instead, the masses excluded are lower than the thermal ones, and whether the GC center would be a more promising target, with respect to dwarves, is at present not clear - and partly motivates this work. The crucial ingredient of indirect detection of EW multiplets is the Sommerfeld enhancement, which we review next.

### 2.2 Sommerfeld-enhanced cross sections

The dominant annihilation channel of the DM triplet and fiveplet, at tree-level, is into pairs of $W^\pm$ bosons, and annihilations into $\gamma$ and $Z$ arise at one loop.\(^1\) Annihilation cross-sections into gauge bosons are enhanced, for non-relativistic relative velocities $v$ and for masses $M_{DM} \gg m_W$, by the so-called Sommerfeld enhancement [34]. This effect grows for smaller velocities, and saturates for $v \lesssim 10^{-2}c$, so that both the Milky Way and the dSph’s belong to the “saturated” regime. The resulting values of the velocity-weighted annihilation cross section $\langle \sigma v \rangle$ (hereafter called annihilation cross section) are shown in figure 1, for all the possible gauge boson final states, and are computed along the lines of [20]. The resonant structure is reminiscent of the presence of bound states of the DM-DM system, due to EW interactions.

\(^1\)Annihilations into SM fermions are extremely suppressed by the fact that the initial DM-DM pair is in a spin 0 state, due to the Majorana nature of DM.
Indeed the exchange of EW gauge bosons leads, in the non-relativistic limit, to an effective attractive (or repulsive, for the dips [35]) potential, which can enhance (or suppress) the tree-level ⟨σv⟩ by orders of magnitude. Notice also the relatively large values of the annihilation cross-section into γγ and in Zγ, responsible for the signal that is the subject of this paper. We refer the reader to [36, 37] for more details about state-of-the-art computations of the Sommerfeld enhancement, and to [38] for a very clear explanation of the effect.

3 Gamma ray lines searches

3.1 Lines accompanied by a continuum

Annihilating DM particles produce γ-rays via prompt emission and secondary radiation. The former refers to all the photons produced at the particle physics level, the latter to the photons coming from interactions, with the galactic medium, of other DM annihilation products. (The main processes giving rise to secondary photons are inverse Compton, bremsstrahlung and synchrotron radiation off e±.)

Concerning the photon energy spectra, they can be roughly classified according to their shape as follows

- γ-ray lines, from the direct annihilation of two DM particles into γγ or γX, e.g. with X = Z. In this case, the spectrum develops a prominent line centered at \( E_\gamma = M_{DM} \).\(^2\)

- γ-ray continuum, a smooth spectrum peaked at energies smaller than \( M_{DM} \) and, depending on its origin, very broad. Such spectra originates both from prompt emission (from the showering, hadronization and decays of the channels in which DM directly annihilates), and from secondary radiation.

\(^2\)γ-ray spectral features other than lines, like for example “boxes” or “triangles”, can also arise in particular models [39, 40], but we will not treat them here.
The focus of this work is on the first kind of spectral shape, γ-ray lines. However, a γ-ray line signal at a given energy would be always accompanied by a broader and lower energy spectrum of photons, because DM generically annihilates to other channels, giving rise to a γ-ray continuum as discussed above. Different relative sizes of the DM annihilation channels lead to different lower energy photon spectra which are, in principle, distinguishable. Supposing a signal in γ-ray lines will be observed, then the size of the continuum with respect to the line and its spread in energy could, in principle (if the relative background can be understood), allow to distinguish between different models in explaining the origin of the line. Also, performing a search for a line plus continuum in photons could allow us to set stronger constraints on a particular model, with respect to a search for γ-ray lines only.

Inspired by the last consideration, in section 5 we will compare the CTA sensitivity to lines-only with respect to that to lines plus continuum. While the line-only analysis can be applied to a large class of DM models, the line plus continuum case requires knowledge of the sizes of all the dominant DM annihilation channels, and thus the specification of a model. We will therefore perform the line plus continuum analysis only for the specific benchmarks of section 2, as an example. In doing so, we will determine the continuum as coming just from the prompt emission, since the secondary radiation for the channel we are interested in (massive EW gauge bosons) is negligible.3

3.2 Fluxes at Earth

For the prompt emission, the differential γ-ray flux at Earth of self-conjugated DM particles, coming from a given angular direction dΩ of the sky, is written as

\[
\frac{d\Phi_\gamma}{d\Omega \, dE_\gamma} = \frac{1}{8\pi M_{DM}^2} \sum_f \langle \sigma v \rangle_f \frac{dN_f}{dE_\gamma} \frac{dJ(\theta)}{d\Omega},
\]

where θ is the angle between the direction to the center of a given astrophysical object and the line of sight (l.o.s.). Here \(dN_f/dE_\gamma\) and \(\langle \sigma v \rangle_f\) are the energy spectrum of photons per one annihilation and the annihilation cross-section into a primary channel \(f\), respectively.

When deriving model-independent sensitivities, the spectrum of photons is simply \(dN_f/dE_\gamma = 2\delta(E_\gamma - M_{DM})\). When considering the DM candidates of section 2 instead, we compute the DM cross-section in a given annihilation mode \(f\) (see figure 1), \(dN_f/dE_\gamma\) by means of the tools provided in [42], and we obtain the total photon spectra

\[
\frac{dN}{dE_\gamma} = \frac{1}{(\sigma v)_{tot}} \sum_f \langle \sigma v \rangle_f \frac{dN_f}{dE_\gamma}.
\]

They are shown with black lines in figure 2. In the left panels of figure 2, we also report the individual contributions to the same spectra, from all the diboson channels. Notice that a line-like feature is given not only by the final states containing a photon, but also by the \(W^+W^-\) one. This is because the radiation of a γ off a \(W^\pm\) is Sudakov-enhanced when the γ takes away all the \(W^\pm\) energy \(M_{DM}\) (apart of course for \(m_W\), explaining the behaviour close to \(M_{DM}\) of the blue lines), see [43] for more details. The difference of this feature from a pure γ line (like the red and orange ones) is however within the energy resolution of both H.E.S.S. and CTA. In the right panels of figure 2, for reference, we provide the total photon spectra also for mass values other than the thermal ones, i.e. 1, 5 and 10 TeV for the Wino,

\[^3\text{Notice that this would not be the case for DM annihilation into } e^+ e^- \text{ and } \mu^+ \mu^- [41].\]
Figure 2. Prompt fluxes of photons. Total photon flux for a given DM mass shown in black. The different contributions to the total photon fluxes are shown, for the thermal masses, in the left-hand panels (colour coding as in figure 1). The right-hand panels show the total photon fluxes only, for different values of the DM mass. Vertical shadings as in figure 1.

and 2.7, 5 and 20 TeV for the 5plet. We choose the first two mass values as examples of different ratios of the cross-section in $W^+W^-$ with respect to other channels (see figure 1), from which the different ratios between the heights of the peak and that of the lower energy continuum, in the right panels of figure 2.

In eq. (3.1) all the information about astrophysics is included in the so called $J$-factor, that sets the normalisation of the $\gamma$-rays fluxes at Earth from different targets. The $J$-factor is the l.o.s. integral of the DM energy density square,

$$\frac{dJ(\theta)}{d\Omega} = \int_{\text{l.o.s.}} \rho_{\text{DM}}^2 [r(s, \theta)] ds,$$

(3.3)

where $s$ is the l.o.s. coordinate. In the next section, we review the targets used in our analysis together with the definition of the regions of interest.
3.3 Galactic Center

Thanks to its vicinity to Earth and to the possible cusp in the DM density distribution, the Galactic Center is often considered to be the most promising laboratory for looking at DM annihilation signals.

**Uncertainties from baryons.** This widespread assumption is challenged by the fact that the mass within the innermost kpc of the Milky Way is dominated by baryons. First, the high density of baryons leads to an expectation of higher astrophysical backgrounds. Second, and perhaps more important for this work, the baryon dominance over DM implies that astronomical observations are far from probing the DM component of the GC (see e.g. [44] but also see [45] for an alternative view), and that numerical simulations need to include hydrodynamics and feedback physics in addition to the gravitational effects, resulting in uncertainties in the obtained DM profiles towards the GC. More precisely, while most hydrodynamical simulations [46–48] agree that the DM profile of MW-like galaxies develops a peak towards the GC, their resolution prevents them from making any statement about the profile for radii smaller than one to a few kpc, a region where the impact of baryons is likely to be even more important. The community has not yet reached an agreement on the best way to model the baryon physics close to the GC, and indeed results in contrast to those previously cited have also been found, such as cores of MW-like galaxies extending to \( \sim 5 \) kpc [49].

**DM profiles in this study.** As long as a clearer determination of the DM profile in the inner MW regions is not achieved, it is worth considering a range of possible choices. Therefore, in our analysis, for the DM density distribution \( \rho_{\text{DM}} \), we consider the cases of Einasto (peaked), Burkert (cored)\(^4\) and NFW with a core \( r_c \) that we are free to vary. For the Einasto and Burkert profiles, the functional forms read

\[
\rho_{\text{Ein}}(r) = \rho_s \exp \left( -\frac{2}{\alpha} \left[ (r/r_s)^{\alpha} - 1 \right] \right),
\]

\[
\rho_{\text{Bur}}(r) = \frac{\rho_s}{\left( 1 + r/r_s \right)^2},
\]

where \( \alpha = 0.17 \). The functional form of the cored NFW is

\[
\rho_{\text{NFW}}(r, r_c) = \begin{cases} 
\frac{\rho_s}{r} \left( 1 + \left( \frac{r_c}{r_s} \right)^{\alpha} \right) & \text{for } r \leq r_c \\
\rho_s & \text{for } r > r_c 
\end{cases},
\]

(3.6)

Once \( r_c \) is fixed, the above functions depend on two free parameters, the typical scale density \( \rho_s \) and the scale radius \( r_s \). One would ideally choose values that match observations of DM properties in the MW, such as the DM density at the Sun position \( \rho_{\odot} \) and the total DM mass within a certain radius. However, precise agreement on the above quantities is still lacking, for recent studies see e.g. [51–53] for \( \rho_{\odot} \), and [53–56] for the DM mass within a given radius. The purpose of this study is not to quantify the impact of the latter uncertainties, so we remain for definiteness with the procedure of [42], fitting the profiles of eqs. (3.4), (3.5), (3.6) to

\[
\rho(r_{\odot} = 8.33 \text{ kpc}) = 0.3 \text{ GeV/cm}^3, \quad M(< 60 \text{ kpc}) = 4.7 \times 10^{11} M_{\odot},
\]

(3.7)

where the values in eq. (3.7) are well within the uncertainties of the observations cited above.

\(^4\)While the choice of a Burkert profile appears to be in contrast with most numerical simulations, it has been argued [50] to be favoured by observations.
### Table 1. GC integrated J-factors, with NFW core radii reported as pedices.

| log$_{10}$ ($J_{\Omega_{\text{obs}}}$ [GeV$^2$/cm$^5$]) | Einasto | Burkert | NFW$_{30}$pc | NFW$_{300}$pc | NFW$_{3kpc}$ |
|--------------------------------------------------|---------|---------|-------------|-------------|-------------|
| 21.15                                            | 21.04   | 20.63   | 19.38       |             |             |

### Table 2. Integrated J-factor together with its statistical errors for each dSph. We also report the celestial location and the mean zenith angle with respect to the location of the CTA sites, using [58].

| Hemisphere | Zenith angle $\theta_z$ | log$_{10}$ ($J_{0.5}$ [GeV$^2$/cm$^5$]) |
|------------|-------------------------|----------------------------------------|
| Draco      | N                       | 18°                                    | 19.09$^{+0.39}_{-0.36}$ |
| Triangulum-II | N                       | 25°                                    | 20.25$^{+1.28}_{-1.56}$ |
| Sculptor   | S                       | 25°                                    | 18.43$^{+0.38}_{-0.17}$ |

### J-factors. We first specify an angular region of observation, centred on the GC, that we define as

$$\Omega_{\text{obs}} = \Omega(\theta < 1^\circ, |b| > 0.3^\circ),$$

where $\theta > 0^\circ$ is the polar angle with respect to the GC direction, and $b$ is the latitude with respect to the galactic disk plane. For convenience of the reader, we also give the corresponding distances from the GC, $1^\circ \approx 145$ pc and $0.3^\circ \approx 44$ pc for $r_\odot = 8.33$ kpc. The region of interest $\Omega_{\text{obs}}$ is the same one chosen by H.E.S.S. for its GC observations [5, 57], and is motivated by the need to mask the large photon backgrounds from the galactic ridge $|b| < 0.3^\circ$, see section 4.1.

We can now evaluate the J-factor of eq. (3.3), integrated over $\Omega_{\text{obs}}$, necessary to compute the total DM annihilation signal from the GC via eq. (3.1). The integrated J-factors we obtain are given in table 1, where for the cored NFW of eq. (3.6) we choose three values of $r_c$ for illustrative purposes.

### 3.4 Dwarf spheroidal galaxies

Dwarf Spheroidal galaxies of the Milky Way are very clean laboratories to look for DM in high energy $\gamma$-rays. They are in fact one of the most DM dominated objects known in the Universe (see [59] and references therein), their baryonic content being very small both in terms of recent stellar formation activity [60, 61] and of interstellar gas medium [62]. After a period of relatively low activity, over which only 9 luminous “classical” dSph galaxies were identified as Milky Way satellites, the field of dSph galaxies is now experiencing a rejuvenation thanks to the Sloan Digital Sky Survey (SDSS) [63], its successor (the Sloan Extension for Galactic Understanding and Evolution (SEGUE) [64]) and to forthcoming imaging surveys such as the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) [65, 66], the Dark Energy Survey (DES) [67, 68] and the forthcoming Large Synoptic Survey Telescope (LSST) [69–71]. The rate of discovery of faint surface-brightness objects, usually called “ultra-faint” dSphs, has been dramatically increasing, making available a relatively large sample of new targets for DM indirect detection.

### Uncertainties in the J-factor determination. Concerning indirect DM detection, the integral of the astrophysical factor in eq. (3.3) is determined by constructing dynamical mass models based on the Jeans equation. Several studies have estimated the J-factor in many
dSphs along with its statistical error [72–75], and several others have used it to constrain the annihilation cross-section of DM [5, 6, 8, 76–80]. In particular, once a specific approach is adopted, the high quality of kinematical data is in general sufficient to provide small statistical errors.\footnote{This is particularly true in the case of “classical” dSphs, which are characterized by a large number of stellar tracers.} Nevertheless, there are crucial systematic uncertainties that come with the determination of the $J$-factor, that are not taken into account in most of these studies (see e.g. section 3.4 of \cite{81}, where a thorough description of the sources of systematic uncertainties is provided). These systematic errors of the theoretical modelling can have a large impact on the determination of the parameters of a given dSph, including the evaluation of the $J$-factor, especially for candidates with a small number of stellar tracers. Therefore it is not surprising that, in the past few months, several papers have tried to address the impact of some of these systematics [82–85].

Choice of the dSphs and $J$-factors. We base our analysis on \cite{82} which evaluates the $J$-factors taking into account the systematic errors coming from non-spherical dark halos, by using axisymmetric mass models. We use this work for two main reasons: \textit{i}) they use the most recent kinematic data of the most complete set of dSphs (7 “classical” and 17 “ultra-faint”); \textit{ii}) they adopt, for the first time, an unbinned analysis for comparison between models and data. This is a more robust and conservative method for constraining dark halo parameters, especially in faint dSph galaxies where the number of stellar tracers is very small.

From their list of dSph galaxies, we choose those with the best $J$-factors. In the northern hemisphere we take the classic dSph Draco and the ultra-faint dSph Triangulum-II. In the southern hemisphere we consider the classical dSph Sculptor. In table 2 we provide, for each dSph, the logarithmic values of the $J$-factor (integrated over 0.5\degree angular annuli surrounding each dSph) together with its statistical error. We also report in the second and third columns the celestial location and zenith angle $\theta_z$ respectively. Notice that, while Draco and Sculptor have hundreds of tracers, the DM properties of Triangulum-II derived in \cite{82} are based only on 13 tracers, making the candidate more speculative cause potentially more subject to systematics.

4 CTA sensitivities

CTA is the forthcoming observatory for $\gamma$-ray astronomy and, in a possible design scenario, it is envisaged to be a two-site array. The northern hemisphere array of CTA, located in Roque de los Muchachos Observatory in La Palma in the Canary Islands, will consist of four large-size (23m diameter) telescopes and 15 medium-size (12m diameter) telescopes. The southern hemisphere array of CTA, located in the European Southern Observatory Cerro Paranal in Chile, would consist of 4 large-size, 24 medium-size and 72 small-size telescopes, in order to cover the full energy range.

CTA performances. CTA will provide excellent angular resolution and very wide energy range with respect to any operating Cherenkov telescope instrument. Although the final configuration of the array is not yet decided, performance studies based on Monte Carlo (MC) simulations have been performed on many candidate arrays, in order to figure out the response functions in terms of flux sensitivity, energy and angular resolutions and background rejection. In the present article, we use the array layout for the southern and northern sites of the CTA observatory as given in \cite{86} (which supersedes previous studies, like \cite{87}, performed when the CTA sites had not been fixed yet).
4.1 DM signals and irreducible backgrounds

The number of photon counts in a given energy bin $\Delta E_i$, for both the signal and the background, is given by

$$N_i^\gamma = \text{observation time} \times \int_{\Delta E_i} \frac{d\Gamma}{dE'}(E', \theta_z) dE',$$

where we express the counting rate as

$$\frac{d\Gamma}{dE'}(E', \theta_z) = \int dE_\gamma A_{\text{eff}}(E_\gamma, \theta_z) \frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma) R(E_\gamma, E').$$

Let us now discuss the different pieces entering the counting rate eq. (4.2).

- $R$ is the energy resolution of the experiment, which we model as a gaussian with variance $\sigma^2$,

$$R(E_\gamma, E') = \frac{1}{2\sqrt{\pi} \sigma(E_\gamma)} \exp \left( -\frac{(E_\gamma - E')^2}{2 \sigma^2(E_\gamma)} \right), \quad \sigma(E_\gamma) = \frac{\delta_{\text{res}}(E_\gamma)}{\sqrt{8 \ln(2)}}$$

where we take $\delta_{\text{res}}$ for the northern and southern sites from [86].

- $A_{\text{eff}}$ is the effective area of the telescope array, where on top of the dependence on the photon energy, we include (for the first time in CTA studies) that on the zenith angle $\theta_z$, because we are interested in targets with different positions in the sky. A dependence on $\theta_z$ is expected because different zenith angles correspond, for the shower, to different thicknesses of atmosphere to cross and to different projections on the telescopes. A $\theta_z$ dependence is indeed taken into account in H.E.S.S., but we are not aware of CTA giving this information. Therefore we assume the effective area of CTA will depend on $\theta_z$ in the same way as the H.E.S.S.-II area, and we extract the H.E.S.S.-II dependence from [89] (see Chapter 4). The CTA effective area then reads

$$A_{\text{eff}}(E_\gamma, \theta_z) = A_{\text{MC}}^{\text{CTA}}(E_\gamma, 0) \times A_{\text{H.E.S.S.-II}}^{\text{HESS,-II}}(E_\gamma, \theta_z) / A_{\text{H.E.S.S.-II}}^{\text{HESS,-II}}(E_\gamma, 0)$$

where $A_{\text{MC}}^{\text{CTA}}(E_\gamma, 0)$ is determined by a CTA MC simulation [86].

- Finally, $d\Phi_\gamma/dE_\gamma$ is the differential photon flux at Earth: $i)$ for the signal, it is given by the integration of eq. (3.1) over the angular regions of interest (see section 3.3 for the GC and section 3.4 for the dSph); $ii)$ for the background, we include two components, one coming from the misidentified interactions of charged CRs ($p$, $e^\pm$, nuclei) with the atmosphere, and one from the diffuse photon background. Modelling of the former is provided by CTA itself in [86], and we stay with that determination. To model the latter, we proceed as in [41] (where the “RoI1” coincides with our $\Omega_{\text{obs}}$) and extrapolate to higher energies the Fermi measurements of photon Galactic Diffuse Emission (GDE) [91, 92], which reach a few hundred GeV. To do so, we assume the photon energy spectrum follows the same power law as the Fermi data. We then...
convolve this determination with the CTA sensitivity. Note that while the misidentified “charged CR” component is isotropic, the “photon diffuse” one quickly drops away from the GC, and is therefore irrelevant for dSph galaxies.

These two background components are shown in figure 3 for the GC region (southern CTA site), together with their sum. We show the backgrounds corresponding to the mean values of the CTA MC simulations, corresponding to the expected means of the sensitivities of section 5. One sees in figure 3 that the inclusion of the photon diffuse component has a non-negligible impact on the total background count. This is the case because the most recent determination of CTA rejections of charged CRs [86], that we are using, substantially improves with respect to previous determinations [87]. We will quantify the impact of the photon diffuse component on the projected sensitivities in section 5.

4.2 Analysis methodology and likelihood

To derive the CTA sensitivity, we perform a likelihood ratio statistical test. The total likelihood $L$ is obtained as a product over the energy bins $i$. For a given $m_{DM}$ and astrophysical target considered in our analysis, we have

$$L(m_{DM}, \langle \sigma v \rangle) = \begin{cases} \prod_{i=1}^{N} L_i(m_{DM}, \langle \sigma v \rangle), & \text{GC} \\ \prod_{i=1}^{N} \max_{J} \left[ L_i(m_{DM}, \langle \sigma v \rangle) \times L^J(J) \right], & \text{dSphs} \end{cases} \tag{4.5}$$

To avoid possible confusion in comparing with the recent [93], notice that there the charged CR background is modeled analytically -as opposed to our direct use of CTA results-, and that their photon backgrounds are not relevant for our study, since they come from the inner GC and from the galactic ridge, that we have masked by choosing the region of observation $\Omega_{obs}$ in eq. (3.8).
where the $N$ energy bins of the counts spectrum are logarithmically spaced between the lower energy threshold of 30 GeV and 80 TeV. Notice that we are not using the spatial information in the likelihood, because the precise spectral location of the line, with respect to the smooth background, provides a discrimination in itself. This agrees with the procedure of H.E.S.S. for $\gamma$ lines searches [5], as opposed to searches for a continuum spectrum, where the spatial information is crucial [41, 81, 94]. Let us now discuss the likelihood terms entering in eq. (4.5).

- Given a set of data $N_{\text{obs}} = \{1, \ldots, N\}$, the individual likelihood $L_i$ in eq. (4.5) is given by a Poisson distribution

$$L_i(N_i | N_{\text{obs}}) = \frac{(N_{\text{obs}})^{N_i}}{N_{\text{obs}}!} e^{-N_i},$$

where $N_{\text{obs}}$ is the sum of the predicted number of events from DM and those from the irreducible backgrounds discussed in section 4.1.

- In the case of dSphs, the term $L^J$ measures the impact of the statistical errors of the $J$-factors. In particular, following [95] we write

$$L^J(J | J_{\text{obs}}, \sigma) = \frac{1}{\ln(10)} J_{\text{obs}} G(\log_{10} J | \log_{10} J_{\text{obs}}, \sigma),$$

where $J_{\text{obs}}$ is the observed $J$-factor of a given dSph, $\sigma$ is the uncertainty on $\log_{10} J_{\text{obs}}$ (both taken from [82]), and $G(x | \mu, \sigma)$ is a Gaussian distribution of mean $\mu$ and standard deviation $\sigma$.

We then maximise the product in eq. (4.5) with respect to the nuisance parameter $J$.

Our statistical analysis then proceeds adopting a likelihood ratio Test Statistic $TS = -2 \ln \left[ \frac{L(m_{DM}, \langle\sigma v\rangle)}{L_{\text{max}}(m_{DM}, \langle\sigma v\rangle)} \right]$, where $L_{\text{max}}$ is maximized over the free parameter $\langle\sigma v\rangle$. We then assume that $TS$ follows a $\chi^2$ distribution, so that, for any $m_{DM}$, values of $TS$ higher than 2.71 are excluded at the 95% confidence level.

To take possible statistical fluctuations of the background into account, we generate a sample of one thousand background counts for each bin, i.e. one thousand sets of the form $N_{\text{bkg}}^{i=\{1, \ldots, N\}}$ (where $N$ is not to be confused with one thousand). To do so, we assume that the number of background events within each bin, $N_{\text{bkg}}^{i}$, vary following a Poissonian distribution. We then perform the likelihood ratio $TS$ for each of the thousand sets generated as above, and we determine the mean expected exclusion as the mean exclusion over this set. We then determine the 68% and 95% containment bands from the 680 and 950 closest lines to the mean expected exclusion.

5 Results and discussion

In what follows, we always assume 100 hours of observation of the GC, and 50 hours of observation of Sculptor, Draco and Triangulum-II. These observation times represent realistic benchmarks, as indeed the GC will arguably be looked at for a longer time than dwarves (keep however in mind the 160 hours of observation of Segue I by MAGIC [8]).

---

9The $J$-factor for the GC is even more uncertain, and we take this into account by showing sensitivities corresponding to much different DM density profiles, see section 3.3.

10The response functions are provided in [86] up to 50 hours of observation, to obtain the sensitivities for 100h we simply rescale the 50h ones by $\sqrt{2}$. 

---
Model independent sensitivities. The expected CTA sensitivities to $\gamma$-ray line signals are shown in figure 4. Notice the wider containment bands of the objects observed by the northern site (Draco and Triangulum-II), compared to those observed by the southern site (GC and Sculptor). This is a consequence of the better sensitivity of the southern site to high energy $\gamma$-rays, thanks also to the higher number of telescopes, which implies higher acceptance and lower residual background. It is also worth pointing out that that all the observational targets in this study lie close to each other in observation angle $\theta_z$, so that the differences induced by this dependence (see eq. (4.4)) are very mild. Concerning the GC, on top of the mean exclusion in dashed, we show as a thinner continuous line what the mean exclusion would have been, if we had not included the photon diffuse emission component of the background, see section 4.1. One sees that the improvement would be
Figure 5. CTA sensitivity vs current exclusions. Dashed lines: expected mean sensitivities of CTA (100 hours, black), H.E.S.S. (112 hours, red) and H.E.S.S.-II (2.8 hours, magenta) observations of the GC, and of Fermi (5.8 years, gray) observations of various MW regions (see text). Points: actual exclusions of H.E.S.S. (circles), H.E.S.S.-II (squares) and Fermi (diamonds), with colour coding and observation times as before. 68% and 95% containment bands shown in magenta and light blue for CTA. Left-hand plot: Einasto profiles for all experiments. Right-hand plot: Burkert profile for H.E.S.S., H.E.S.S.-II and CTA, Isothermal for Fermi.

Comparison with existing limits. With respect to presently existing bounds for γ-ray lines, CTA will constitute a major improvement. The only existing bound on γ-ray lines from dSph has been derived by MAGIC [8], from 160 hours of observation of the dSph Segue I. However, the estimate of its J-factor has dropped by roughly two orders of magnitudes [75, 82], compared to the one derived by MAGIC and used to cast their exclusion limits. Therefore, we refrain from showing the MAGIC exclusion on the same figures as our projections. Concerning the GC, we show in figure 5 how our projected CTA sensitivities compare with existing bounds from Fermi [6], H.E.S.S. [5] and H.E.S.S.-II [7]. We show as points the actual limits, and as continuous lines the expected limits corresponding to those points, to guide the eye in the comparison with CTA. H.E.S.S. and H.E.S.S.-II observed the same region \( \Omega_{\text{obs}} \) of our study, and in figure 5 we have rescaled the existing bounds to be consistent with our choices of DM profile (see section 3.3), being \( J_{\text{HESS}}^{\text{obs}} = 4.4 \times 10^{21} \text{ GeV}^2/\text{cm}^2 \). The regions of interest of Fermi change from ours, and we simply report the limits as they give them, for two choices that appear most similar to ours, i.e. an Einasto and an Isothermal profiles. The respective regions of interest, called “R16” and “R90”, are optimized for the related DM profiles, and are much more extended than our \( \Omega_{\text{obs}} \). This in particular explains the much better Fermi sensitivity with a cored (Isothermal) profile, which comes from its capability to observe a very large sky region.

Dwarf Spheroidal galaxies versus Galactic Center. The poor knowledge of the DM density profile, as substantiated in section 3.3, makes it necessary to include this uncertainty when comparing the GC with other targets, like dSphs. We do so by being agnostic on the...
Figure 6. Galactic Center vs. dwarf spheroidals. CTA sensitivity to monochromatic photons from the GC (100 hours of observation), Triangulum-II (50 hours) and Draco (50 hours), as a function of the core radius of the NFW DM profile of the Milky Way, up to the Sun position. Left-hand plot: DM mass of 2.9 TeV (Wino thermal mass). Right-hand plot: DM mass of 9.4 TeV (5plet thermal mass).

The size of a possible core radius of the DM distribution in the MW: in figure 6 we show the projected CTA sensitivities to $\gamma$-lines, from Triangulum-II, Draco and the GC\footnote{We do not show Sculptor because of its poorer reach, compared to the other two dSphs. Notice then that in figure 6 we are comparing observations made by the northern CTA site (the dSphs) with others made by the southern site (the GC).} with the assumption of a cored NFW density profile, as a function of the core radius $r_c$. We do so for two representative values of the DM mass, corresponding to the thermal masses of Wino DM and of the MDM 5plet.

One sees in figure 6 that the sensitivity from 100 hours of GC observations is expected to be comparable with that of 50 hours of observation of a dSph like Triangulum-II if the DM distribution develops a core around one kpc, a possibility well allowed by both observations and numerical DM simulations. For a dwarf like Draco to constitute a better target than the GC, the DM distribution should instead have a core which extends to a few kpc, the mean expected sensitivities of the GC and Draco crossing around 4 kpc. We remind the reader that while observationally such large cores are perfectly viable (and possibly favored), they are in some tension with most numerical simulations, see section 3.3.

CTA sensitivity to electroweak multiplets. Finally, we show in figure 7 our mean expected CTA reaches compared with the predictions of the two benchmarks discussed in section 2, the Wino DM and the MDM 5-plet. 100 hours of observations of the GC would probe the thermal masses of both candidates, if one will be able to firmly exclude the presence of a DM core of several kpc. Concerning dSphs, 50 hours of observation of Triangulum-II have the potential to largely exclude, or discover, both thermal candidates. This last statement is however subject to a collection of more kinematical data regarding Triangulum-II, necessary to confirm or disprove its potential for DM indirect detection. Draco has instead only the potential to marginally test the MDM 5-plet. The prospects of CTA searches for monochromatic $\gamma$-ray lines, for values of $M_{DM}$ others than the thermal ones, are also readable.
Figure 7. EW multiplets with CTA. Continuous black lines: theoretical prediction of the cross section into monochromatic photons \( \langle \sigma v \rangle_{\gamma \gamma + Z/2} \), for Wino DM (left) and MDM 5plet (right). Overlaid lines: mean expected CTA sensitivities for 50 hours of observation of Draco (dot-dashed orange) and Triangulum-II (dotted orange), and for 100 hours of observation of the GC, for a Burkert (dot-dashed magenta) and an Einasto (dotted magenta) profiles. Vertical shadings as in figure 1. The horizontal lines within the vertical shading represent the improvement in sensitivity of each target, at that mass value, from taking into account the lower energy photon continuum spectra, on top of the \( \gamma \)-ray line.

off figure 7. Concerning CTA prospects for \( \gamma \) lines from the GC, in recent literature they have been given for both Wino [96, 97] and fiveplet [20, 98] DM. The mild differences with respect to our work are ascribable to the use of previous determinations of CTA sensitivities by those works [93, 99], as well as to the choice of different DM profiles.

For the specific thermal mass values, and for the specific predictions of the Wino and fiveplet, we show also the results of a continuum plus line analysis, see sections 3.1 and 4.2. One sees in figure 7 that such a model-dependent analysis has the potential to improve the sensitivities by a few tens of percent, with respect to the sensitivities to \( \gamma \)-ray lines only. We conservatively choose not to include the prospects for this specific analysis in the case of a Burkert profile, because searches for a \( \gamma \)-ray continuum from the GC have so far required a morphological analysis. This is based on the ON-OFF technique for signal vs background discrimination, which is only reliable for cuspy DM profiles [41, 94].

6 Summary and conclusions

In this paper we have provided CTA sensitivities to \( \gamma \)-ray line features, from the observation of both the GC and, for the first time, of dSphs. We have chosen Triangulum-II, Draco, and Sculptor as most promising (according to [82]) candidates. Our results can be summarised as follows:

- Concerning the analysis, we have performed it with the most updated instrument response functions and cosmic-ray background estimates, provided by CTA in [86]. On top of this irreducible background, for the GC we have added the photon diffuse component, obtained by extrapolating the Fermi measurements [91, 92] at higher energies, that we have found to be non-negligible (see figure 3). The latest CTA improved estimate concerning background rejections plays a key role in this conclusion. However,
the impact of the diffuse photon component on the expected sensitivities is mild, see figure 4.

- Concerning the expected sensitivities, we have compared them with the current available limits from the GC, finding a factor of improvement of a few-to-ten in the TeV range, see figure 5. Searches of $\gamma$ lines from dSph are today an almost unexplored avenue, and we have shown their potential by comparing their reach with that of the GC, as a function of a putative coring radius of the DM distribution, see figure 6. We have found that the GC becomes a less promising target than Triangulum-II if a core extends up to roughly one kpc, and than Draco if a core extends up to a few kpc. We remind the reader that cores of several kpc appear to be in conflict with most [46–48] (but not all [49]) numerical simulations, and are instead perfectly allowed [44] by observations. We also remark that more tracers are needed to establish Triangulum-II as “the” target for future observations, in particular because of the small number of tracers (13) on which its study [82] (see also [85]) is based. We have chosen it nonetheless as an example of the potential of dSphs, because more observations will hopefully increase the number of observed tracers, and because future surveys (such as Pan-STARRS [65, 66], DES [67, 68] and LSST [69–71]) are expected to discover a plethora of new dwarf satellites of our galaxy.

- Concerning the specific candidates of SUSY Wino and MDM 5plet, we have compared their predictions with our sensitivities in figure 7. CTA has the potential to discover or rule out their thermal relic origin, unless the prospects for Triangulum-II will be substantially scaled down, and the existence of a several kpc core in the DM distribution will not be excluded. We have also performed, for the first time, a dedicated analysis that includes the model-dependent information about the lower-energy continuum photon spectrum of such models, for specific thermal mass values. We find that a similar analysis has the potential to increase the cross section reach by a few tens of percent.

Our results challenge the widespread claim that the Galactic Center is the best target for the quest for $\gamma$ lines from DM annihilations, and underline the importance of achieving a better knowledge of the DM density profile in the inner kiloparsecs of the Milky Way. They further motivate dedicating observation time of CTA to dwarf Spheroidal galaxies. The analysis presented in this paper also constitutes a valuable complement to physics studies of future high energy colliders, which invoke strong motivation via the search for TeV-mass DM candidates [27].

Acknowledgments

We thank Arianna Di Cintio, Jose Oñorbe, Miguel Pato and Aion Viana for useful discussions. P.P. is grateful to the Laboratoire de Physique Théorique et Hautes Energies (LPTHE) for hospitality. F.S. is grateful to the Institut d’Astrophysique de Paris (IAP) for hospitality, and to the Mainz Institute for Theoretical Physics (MITP) for hospitality and support.

Funding and research infrastructure acknowledgements:

* European Research Council (Erc) under the EU Seventh Framework Programme (FP7/2007-2013)/Erc Starting Grant (agreement n. 278234 — ‘NEWDARK’ project),
* Erc Advanced Grant 267117 (‘DARK’) hosted by Université Pierre & Marie Curie — Paris 6.
References

[1] HESS, http://www.mpi-hd.mpg.de/hfm/HESS/ (2003).
[2] MAGIC, http://www.magic.mppmu.mpg.de/ (2003).
[3] VERITAS, http://veritas.sao.arizona.edu/ (2007).
[4] CTA CONSORTIUM collaboration, M. Actis et al., Design concepts for the Cherenkov Telescope Array CTA: an advanced facility for ground-based high-energy gamma-ray astronomy, Exper. Astron. 32 (2011) 193 [arXiv:1008.3703] [inSPIRE].
[5] H.E.S.S. collaboration, A. Abramowski et al., Search for photon-linelike signatures from dark matter annihilations with H.E.S.S., Phys. Rev. Lett. 110 (2013) 041301 [arXiv:1301.1173] [inSPIRE].
[6] Fermi-LAT collaboration, M. Ackermann et al., Updated search for spectral lines from Galactic dark matter interactions with pass 8 data from the Fermi Large Area Telescope, Phys. Rev. D 91 (2015) 122002 [arXiv:1506.00013] [inSPIRE].
[7] H.E.S.S. collaboration, M. Kieffer J. Veh et al., Search for gamma-ray line signatures with H.E.S.S, PoS(ICRC2015)1229 [arXiv:1509.03514] [inSPIRE].
[8] J. Aleksić et al., Optimized dark matter searches in deep observations of Segue 1 with MAGIC, JCAP 02 (2014) 008 [arXiv:1312.1535] [inSPIRE].
[9] G.F. Giudice, M.A. Luty, H. Murayama and R. Rattazzi, Gaugino mass without singlets, JHEP 12 (1998) 027 [hep-ph/9810442] [inSPIRE].
[10] J.D. Wells, Implications of supersymmetry breaking with a little hierarchy between gauginos and scalars, in the proceedings of the 11th International Conference on Supersymmetry and the Unification of Fundamental Interactions (SUSY 2003), June 5–10, Tucson, Arizona (2003), hep-ph/0306127 [inSPIRE].
[11] N. Arkani-Hamed and S. Dimopoulos, Supersymmetric unification without low energy supersymmetry and signatures for fine-tuning at the LHC, JHEP 06 (2005) 073 [hep-th/0405159] [inSPIRE].
[12] G.F. Giudice and A. Romanino, Split supersymmetry, Nucl. Phys. B 699 (2004) 65 [Erratum ibid. B 706 (2005) 487] [hep-ph/0406088] [inSPIRE].
[13] F. D’Eramo, L.J. Hall and D. Pappadopulo, Multiverse Dark Matter: SUSY or axions, JHEP 11 (2014) 108 [arXiv:1409.5123] [inSPIRE].
[14] M. Cirelli, F. Sala and M. Taoso, Wino-like minimal dark matter and future colliders, JHEP 10 (2014) 033 [Erratum ibid. 01 (2015) 041] [arXiv:1407.7058] [inSPIRE].
[15] L. Di Luzio, R. Gröber, J.F. Kamenik and M. Nardecchia, Accidental matter at the LHC, JHEP 07 (2015) 074 [arXiv:1504.00359] [inSPIRE].
[16] E. Del Nobile, M. Nardecchia and P. Panci, Millicharge or decay: a critical take on minimal dark matter, JCAP 04 (2016) 048 [arXiv:1512.05353] [inSPIRE].
[17] M. Cirelli, N. Fornengo and A. Strumia, Minimal dark matter, Nucl. Phys. B 753 (2006) 178 [hep-ph/0512090] [inSPIRE].
[18] M. Cirelli and A. Strumia, Minimal dark matter: model and results, New J. Phys. 11 (2009) 105005 [arXiv:0903.3381] [inSPIRE].
[19] M. Beneke et al., Relic density of wino-like dark matter in the MSSM, JHEP 03 (2016) 119 [arXiv:1601.04718] [inSPIRE].
[20] M. Cirelli, T. Hambye, P. Panci, F. Sala and M. Taoso, Gamma ray tests of minimal dark matter, JCAP 10 (2015) 026 [arXiv:1507.05519] [inSPIRE].
[21] J. Hisano, S. Matsumoto, M. Nagai, O. Saito and M. Senami, Non-perturbative effect on thermal relic abundance of dark matter, *Phys. Lett. B* **646** (2007) 34 [hep-ph/0610249] [inSPIRE].

[22] T. Moroi and L. Randall, Wino cold dark matter from anomaly mediated SUSY breaking, *Nucl. Phys. B* **570** (2000) 455 [hep-ph/9906527] [inSPIRE].

[23] G.F. Giudice, E.W. Kolb and A. Riotto, Largest temperature of the radiation era and its cosmological implications, *Phys. Rev. D* **64** (2001) 023508 [hep-ph/0005123] [inSPIRE].

[24] ATLAS collaboration, Search for charginos nearly mass degenerate with the lightest neutralino based on a disappearing-track signature in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, *Phys. Rev. D* **88** (2013) 112006 [arXiv:1310.3675] [inSPIRE].

[25] CMS collaboration, Search for disappearing tracks in proton-proton collisions at $\sqrt{s} = 8$ TeV, *JHEP* **01** (2015) 096 [arXiv:1411.6006] [inSPIRE].

[26] M. Low and L.-T. Wang, Neutralino dark matter at 14 TeV and 100 TeV, *JHEP* **08** (2014) 161 [arXiv:1404.0682] [inSPIRE].

[27] J. Hisano, K. Ishiwata and N. Nagata, QCD effects on direct detection of Wino dark matter, *JHEP* **06** (2015) 097 [arXiv:1504.00915] [inSPIRE].

[28] P. Cushman et al., Working Group Report: WIMP Dark Matter Direct Detection, talk given at Community Summer Study 2013: snowmass on the Mississippi (CSS2013), July 29–August 6, Minneapolis, U.S.A. (2013), arXiv:1310.8327 [inSPIRE].

[29] M. Baumgart and V. Vaidya, Semi-inclusive wino and higgsino annihilation to LL', *JHEP* **03** (2016) 213 [arXiv:1510.02470] [inSPIRE].

[30] M. Beneke, C. Hellmann and P. Ruiz-Femenia, Non-relativistic pair annihilation of nearly mass degenerate neutralinos and charginos III. Computation of the Sommerfeld enhancements, *JHEP* **05** (2015) 115 [arXiv:1411.6924] [inSPIRE].

[31] N. Arkani-Hamed, D.P. Finkbeiner, T.R. Slatyer and N. Weiner, A theory of dark matter, *Phys. Rev. D* **79** (2009) 015014 [arXiv:0810.0713] [inSPIRE].

[32] A. Ibarra, S. Lopez Gehler and M. Pato, Gamma-ray triangles: a possible signature of asymmetric dark matter in indirect searches, arXiv:1604.01899 [inSPIRE].
[41] V. Lefranc, E. Moulin, P. Panci and J. Silk, Prospects for annihilating dark matter in the inner galactic halo by the Cherenkov Telescope Array, Phys. Rev. D 91 (2015) 122003 [arXiv:1502.05064] [inSPIRE].

[42] M. Cirelli et al., PPPC 4 DM ID: a Poor Particle Physicist Cookbook for Dark Matter Indirect Detection, JCAP 03 (2011) 051 [Erratum ibid. 10 (2012) E01] [arXiv:1012.4515] [inSPIRE].

[43] P. Ciafaloni, D. Comelli, A. Riotto, F. Sala, A. Strumia and A. Urbano, Weak corrections are relevant for dark matter indirect detection, JCAP 03 (2011) 019 [arXiv:1009.0224] [inSPIRE].

[44] F. Iocco, M. Pato and G. Bertone, Evidence for dark matter in the inner Milky Way, Nature Phys. 11 (2015) 245 [arXiv:1502.03821] [inSPIRE].

[45] C. Wegg, O. Gerhard and M. Portail, MOA-II galactic microlensing constraints: the inner Milky Way has a low dark matter fraction and a near maximal disk, arXiv:1607.06462 [inSPIRE].

[46] A. Di Cintio et al., The dependence of dark matter profiles on the stellar-to-halo mass ratio: a prediction for cusps versus cores, Mon. Not. Roy. Astron. Soc. 437 (2014) 415 [arXiv:1306.0898] [inSPIRE].

[47] F. Iocco, M. Pato and G. Bertone, Dynamical constraints on the dark matter distribution in the Milky Way, JCAP 12 (2015) 001 [arXiv:1504.06324] [inSPIRE].

[48] M. Pato and F. Iocco, Mapping dark matter in the Milky Way, a synopsis, PoS(ICRC2015)023 [arXiv:1511.05571] [inSPIRE].

[49] Y. Huang et al., The Milky Way’s rotation curve out to 100 kpc and its constraint on the Galactic mass distribution, to be published in Mon. Not. Roy. Astron. Soc. [arXiv:1604.01216].

[50] M. Boylan-Kolchin, J.S. Bullock, S.T. Sohn, G. Besla and R.P. van der Marel, The space motion of Leo I: the mass of the Milky Way’s dark matter halo, Astrophys. J. 768 (2013) 140 [arXiv:1210.6046] [inSPIRE].

[51] https://www.mpi-hd.mpg.de/hfm/HESS/public/Visibility.html.
[60] D.R. Weisz et al., The ACS nearby galaxy survey treasury VIII. The global star formation histories of 60 dwarf galaxies in the local volume, *Astrophys. J.* **739** (2011) 5 [arXiv:1101.1093] [inSPIRE].

[61] T.M. Brown et al., The primeval populations of the ultra-faint dwarf galaxies, *Astrophys. J.* **753** (2012) L21 [arXiv:1206.0941] [inSPIRE].

[62] M. Mateo, Dwarf galaxies of the local group, *Ann. Rev. Astron. Astrophys.* **36** (1998) 435 [astro-ph/9810070] [inSPIRE].

[63] SDSS collaboration, K.N. Abazajian et al., The seventh data release of the Sloan Digital Sky Survey, *Astrophys. J.* **182** (2009) 543 [arXiv:0812.0649] [inSPIRE].

[64] SDSS-II SEGUE collaboration, B. Yanny et al., SEGUE: a spectroscopic survey of 240,000 stars with $g = 14$–20, *Astron. J.* **137** (2009) 4377 [arXiv:0902.1781] [inSPIRE].

[65] Pan-STARRS, http://pan-starrs.ifa.hawaii.edu/public/ (2008).

[66] N. Kaiser et al., Pan-STARRS: a large synoptic Survey Telescope ARRay, *Proc. SPIE Int. Soc. Opt. Eng.* **4836** (2002) 154.

[67] Dark Energy Survey, http://www.darkenergysurvey.org/ (2008).

[68] Dark Energy Survey collaboration, B. Flaugher, The Dark Energy Survey, *Int. J. Mod. Phys. A* **20** (2005) 3121 [inSPIRE].

[69] LSST, http://www.lsst.org/lsst/ (2008).

[70] J.A. Tyson, D.M. Wittman, J.F. Hennawi and D.N. Spergel, LSST: a complementary probe of dark energy, *Nucl. Phys. Proc. Suppl.* **124** (2003) 21 [astro-ph/0209632] [inSPIRE].

[71] J.R. Hargis, B. Willman and A.H.G. Peter, Too many, too few, or just right? The predicted number and distribution of Milky Way dwarf galaxies, *Astrophys. J.* **795** (2014) L13 [arXiv:1407.4470] [inSPIRE].

[72] L.E. Strigari M. Geha et al., The most dark matter dominated galaxies: predicted gamma-ray signals from the faintest Milky Way dwarfs, *Astrophys. J.* **678** (2008) 614 [arXiv:0709.1510] [inSPIRE].

[73] G.D. Martinez, A robust determination of Milky Way satellite properties using hierarchical mass modelling, *Mon. Not. Roy. Astron. Soc.* **451** (2015) 2524 [arXiv:1309.2641] [inSPIRE].

[74] A. Geringer-Sameth, S.M. Koushiappas and M. Walker, Dwarf galaxy annihilation and decay emission profiles for dark matter experiments, *Astrophys. J.* **801** (2015) 74 [arXiv:1408.0002] [inSPIRE].

[75] V. Bonnivard et al., Dark matter annihilation and decay in dwarf spheroidal galaxies: The classical and ultrafaint dSphs, *Mon. Not. Roy. Astron. Soc.* **453** (2015) 849 [arXiv:1504.02048] [inSPIRE].

[76] N.W. Evans, F. Ferrer and S. Sarkar, A ‘Baedecker’ for the dark matter annihilation signal, *Phys. Rev. D* **69** (2004) 123501 [astro-ph/0311145] [inSPIRE].

[77] R. Essig, N. Schgal and L.E. Strigari, Bounds on cross-sections and lifetimes for dark matter annihilation and decay into charged leptons from gamma-ray observations of dwarf galaxies, *Phys. Rev. D* **80** (2009) 023506 [arXiv:0902.4750] [inSPIRE].

[78] A. Geringer-Sameth and S.M. Koushiappas, Exclusion of canonical WIMPs by the joint analysis of Milky Way dwarfs with Fermi, *Phys. Rev. Lett.* **107** (2011) 241303 [arXiv:1108.2914] [inSPIRE].

[79] A. Charbonnier et al., *Mon. Not. Roy. Astron. Soc.* **418** (2011) 1526 [arXiv:1104.0412].

[80] Fermi-LAT collaboration, M. Ackermann et al., Searching for dark matter annihilation from Milky Way dwarf spheroidal galaxies with six years of Fermi Large Area Telescope data, *Phys. Rev. Lett.* **115** (2015) 231301 [arXiv:1503.02641] [inSPIRE].
Prospects for annihilating Dark Matter towards Milky Way’s dwarf galaxies by the Cherenkov Telescope Array, *JCAP* 09 (2016) 021 [arXiv:1605.02793] [SPIRE].

Dark matter annihilation and decay from non-spherical dark halos in the Galactic dwarf satellites, *Mon. Not. Roy. Astron. Soc.* 461 (2016) 2914 [arXiv:1603.08046] [SPIRE].

A critical reassessment of particle Dark Matter limits from dwarf satellites, *JCAP* 07 (2016) 025 [arXiv:1603.07721] [SPIRE].

Simple J-factors and D-factors for indirect dark matter detection, *Phys. Rev. D* 93 (2016) 103512 [arXiv:1604.05599] [SPIRE].

The potential of the dwarf galaxy Triangulum II for dark matter indirect detection, arXiv:1604.00838 [SPIRE].

Monte Carlo design studies for the Cherenkov Telescope Array, *Astropart. Phys.* 43 (2013) 171 [arXiv:1210.3503] [SPIRE].

Observations of the Crab Nebula with H.E.S.S, *Astron. Astrophys.* 457 (2006) 899 [astro-ph/0607333] [SPIRE].

Détectuon du pulsar de Vela et recherche de violation d’invariance de Lorentz avec le cinquième téloscope de H.E.S.S., Ph.D. Thesis, Université Pierre et Marie Curie — Paris VI, Paris, France (2016).

A realistic assessment of the CTA sensitivity to dark matter annihilation, *JCAP* 03 (2015) 055 [arXiv:1408.4131] [SPIRE].

Fermi-LAT observations of the diffuse gamma-ray emission: implications for cosmic rays and the interstellar medium, *Astrophys. J.* 750 (2012) 3 [arXiv:1202.4039] [SPIRE].

The spectrum of isotropic diffuse gamma-ray emission between 100 MeV and 820 GeV, *Astrophys. J.* 799 (2015) 86 [arXiv:1410.3696] [SPIRE].

On the sensitivity of CTA to gamma-ray boxes from multi-TeV dark matter, *JCAP* 09 (2015) 048 [arXiv:1503.06797] [SPIRE].

Search for a Dark Matter annihilation signal from the Galactic Center halo with H.E.S.S, *Phys. Rev. Lett.* 106 (2011) 161301 [arXiv:1103.3266] [SPIRE].

Constraining dark matter models from a combined analysis of Milky Way satellites with the Fermi Large Area Telescope, *Phys. Rev. Lett.* 107 (2011) 241302 [arXiv:1108.3546] [SPIRE].

Heavy dark matter annihilation from effective field theory, *Phys. Rev. Lett.* 114 (2015) 211302 [arXiv:1409.8294] [SPIRE].

Electro-weak dark matter: non-perturbative effect confronting indirect detections, *Phys. Lett. B* 750 (2015) 372 [arXiv:1506.07522] [SPIRE].

Gamma-rays from Heavy Minimal Dark Matter, *JCAP* 10 (2015) 058 [arXiv:1507.05536] [SPIRE].

Investigating gamma-ray lines from dark matter with future observatories, *JCAP* 11 (2012) 025 [arXiv:1207.6773] [SPIRE].