

# Could the Fermi Large Area Telescope detect $\gamma$ -rays from dark matter annihilation in the dwarf galaxies of the Local Group?

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## ABSTRACT

**Context.** The detection of  $\gamma$ -rays from dark matter (DM) annihilation is among the scientific goals of the Fermi Large Area Telescope (formerly known as GLAST) and Cherenkov telescopes.

**Aims.** In this paper we investigate the chances of such a discovery, selecting some nearby dwarf spheroidal galaxies (dSph) as a target, and adopting the DM density profiles derived from both astronomical observations and  $N$ -body simulations. We also make use of recent studies about the presence of black holes and of a population of sub-subhalos inside the Local Group (LG) dwarfs to carry out boost factor studies.

**Methods.** We study the detectability with the Fermi-LAT of the  $\gamma$ -ray flux from DM annihilation in four of the nearest and highly DM-dominated dSph galaxies of the LG, namely Draco, Ursa Minor, Carina, and Sextans, for which state-of-art DM density profiles were available. We assume the DM is made of weakly interacting massive particles such as the lightest supersymmetric particle and compute the expected  $\gamma$ -ray flux for estimations of the unknown underlying particle physics parameters. We then compute the boost factors due to the presence of DM clumps and of a central supermassive black hole. Finally, we compare our predictions with the Fermi-LAT sensitivity maps.

**Results.** We find that the dSph galaxies shine above the Galactic smooth halo: e.g., the Galactic halo is brighter than the Draco dSph only for angles smaller than 2.3 degrees above the Galactic Center. We also find that the presence of a cusp or a constant density core in the DM mass density profile does not produce any relevant effects in the  $\gamma$ -ray flux due to the fortunate combination of the geometrical acceptance of the Fermi-LAT detector and the distance of the galaxies. Moreover, no significant enhancement is given by the presence of a central black hole or a population of sub-subhalos.

**Conclusions.** We conclude that, even for the most optimistic scenario of particle physics, the  $\gamma$ -ray flux from DM annihilation in the dSph galaxies of the LG would be too low to be detected with the Fermi-LAT.

**Key words.** galaxies: halos – galaxies: Local Group – galaxies: dwarf – cosmology: dark matter – gamma rays: observations – gamma rays: theory

## 1. Introduction

Since the first evidence of the presence of dark matter (DM) in the universe, scientists have worked to understand its nature and distribution. This investigation involves different fields of research such as particle physics, cosmology and, observational astronomy (e.g. Bahcall et al. 1999; Spergel et al. 2003).

The Fermi Large Area Telescope (Fermi-LAT) will test theories in which DM candidates are the lightest supersymmetric particles (LSPs) such as the neutralinos, arising in supersymmetric extensions of the Standard Model of particle physics (SUSY), or the lightest Kaluza-Klein particles (LKKPs) such as the  $B^{(1)}$ s, first excitation of the hypercharge gauge boson in theories with universal extra dimensions (see Bergström 2000; Bertone et al. 2005, and references therein). Typical values for the mass of these candidates range from about 50 GeV up to several TeV.

Cosmological models, mainly based on  $N$ -body simulations in a  $\Lambda$ -cold dark matter (CDM) framework, successfully reproduce relevant characteristics of the universe such as the cosmic microwave background anisotropy and the large scale structure of the universe. They also predict well-defined properties of DM haloes, whose radial mass density distribution follows a

universal law, and it is described by a steep power law for a wide range of masses ranging from dwarf galaxies to galaxy clusters (see, e.g., Navarro et al. 1996, 1997, 2004; Moore et al. 1998, 1999; Diemand et al. 2005). However, the astronomical community is still debating whether DM haloes are characterized by a central density cusp. In fact, haloes with a constant density core are in most cases preferred to account for the observed kinematics of galaxies (see Binney 2004, for a review).

Generally speaking, the uncertainty in the choice of the density profile can result in several orders of magnitude of uncertainty in the  $\gamma$ -ray flux prediction, which already suffers from the high uncertainties arising from the unknown underlying particle physics (Fornengo et al. 2004). For this reason it would be important to derive the DM density profile of galaxies directly from the available kinematic data. Although data-sets for the very inner part of the galaxies are scarce and affected by large errors, the situation is not better in  $N$ -body simulations, whose resolution goes down to 0.05 times the virial radius at most. Using real data we have the advantage of deriving a flux prediction which takes into account the peculiarity of each galaxy, without any model-dependent generalization which would increase the astrophysical uncertainties.

The expected  $\gamma$ -ray flux at the telescope from a given source is directly proportional to the DM density squared along the line-of-sight (LOS), and inversely proportional to the square of its distance. The best targets are therefore nearby dense objects such as the local dwarf spheroidal galaxies (see [Mateo 1998](#), for a review). Indeed, in the last decade, the large collecting area of the 8-m class telescopes and the use of multi-fiber spectrographs have allowed astronomers to obtain high-resolution spectra of a large number of stars. This made it possible to isolate the galaxy member stars, to measure their radial velocity with an accuracy of a few  $\text{km s}^{-1}$  and to build accurate dynamical models of a number of such systems (see [Gilmore et al. 2007](#), and references therein).

Annihilation of  $\gamma$ -rays in dSph galaxies would give a clean signal because of the absence of high astrophysical uncertainties in modeling the expected background and could hopefully be detected with upcoming experiments like the Fermi-LAT. Many authors have studied the feasibility of such a detection, using a large variety of cuspy and cored universal density profiles, reflecting the theoretical as well as the experimental uncertainties. Different works ([Baltz et al. 2000](#); [Tyler 2002](#); [Peirani et al. 2004](#); [Pieri & Branchini 2004](#); [Bergström et al. 2006](#)) found that only the presence of a spike and/or an enhancement due to clumpiness and/or a more favourable combination of the unknown particle physics parameters could make the Draco dwarf galaxy observable with the Fermi-LAT. [Strigari et al. \(2007\)](#) are optimistic about the detection of Draco with the Fermi-LAT in 5 years. They adopted a King profile ([King 1966](#)) to derive the surface density of the stellar luminosity. This was deprojected and converted into the stellar mass density by adopting the typical range of the mass-to-light ratio of dSphs. The luminous mass they derived is at the very least one order of magnitude below the mass of the DM halo. For the halo they assumed an NFW mass density profile ([Navarro et al. 1996, 1997](#)) whose free degenerate parameters were constrained by marginalizing over the stellar velocity dispersion anisotropy parameter. [Colafrancesco et al. \(2007\)](#) showed how diffuse radio emission would actually be a more promising process to look at in order to detect a DM signal. They also claimed that the presence of a supermassive black hole (SBH) at the centre of Draco, which could enhance the  $\gamma$ -ray signal up to detectable levels, is not actually excluded by experiments. Detection of annihilation  $\gamma$ -rays from Draco has been excluded by [Sánchez-Conde et al. \(2007\)](#) through the use of density profiles that are compatible with the latest observations.

In this paper we use the latest available astrophysical measurements for four of the nearest and highly DM-dominated dSph galaxies of the Local Group, namely Draco, Ursa Minor, Carina, and Sextans to compute the expected  $\gamma$ -ray flux from DM annihilation.

In Sect. 2 the most optimistic particle physics scenarios and the DM density profiles derived both from the available kinematic measurements and from  $N$ -body simulations are used to predict the expected  $\gamma$ -ray flux from DM annihilation in Draco, Ursa Minor, Carina, and Sextans. In Sect. 3 the predicted flux is compared with the experimental sensitivity of the Fermi-LAT. The presence of DM clumps and a central SBH could enhance the  $\gamma$ -ray flux. But their effects have to be rescaled for the limits imposed on the extragalactic  $\gamma$ -ray background (EGB) by the Energetic Gamma-Ray Experiment (EGRET) and on the  $\gamma$ -ray flux in Draco by the measurements of the Major Atmospheric Gamma-Ray Imaging Cherenkov (MAGIC) telescope. Our conclusions are given in Sect. 4.

The main differences with the other papers discussed above are the following: we show that, even adopting a very favorable case for the unknown particle physics sector, the expected flux from the DM halo is about two orders of magnitude below the detectability limit of the Fermi-LAT experiment; we also show how the use of a cored or a cuspy profile does not produce any relevant effect in the expected  $\gamma$ -ray flux, because of a combination of the galaxy distance and the angular acceptance of the Fermi-LAT; we then show that the current limits on the mass of the supermassive black hole (SMBH) inside Draco lead to an insignificant boost factor due to the presence of such a SMBH; and we numerically compute the boost factor due to the presence of a population of subhaloes inside the dwarf galaxies, limiting the possible range of models for the subhalo structure making use of the constraints imposed by the EGRET extragalactic measurements; the boost factor due to the presence of sub-subhaloes is computed in two ways: first, we obtain it integrating over the whole volume of the galaxy, as done, e.g., in [Strigari et al. \(2007\)](#). This gives the correct boost factor when considering cosmological haloes. But, if we consider the closer dwarf galaxies, we have to take into account that only the very inner part of the galaxy is observed within the angular resolution of the instrument. We therefore also compute the angular dependence of the boost factor due to sub-subhaloes. Although we find a huge enhancement of the flux far from the galaxy center, there is actually no enhancement along the LOS pointing toward the galaxy center. As a last improvement with respect to the other papers, we compare our predictions with a recently released detectability map for the Fermi-LAT which takes into account the response of the detector to different energies and incidence angles, as far as effective energy and angular resolution are concerned.

## 2. $\gamma$ -ray flux from dark matter annihilation

The  $\gamma$ -ray flux  $\Phi_\gamma$  from DM annihilation can be factorized into a term  $\Phi_{\text{PP}}$  involving the particle physics and a term  $\Phi_{\text{cosmo}}$  where astrophysics, cosmology, and experimental geometry play the main role. It is

$$\Phi_\gamma(E_\gamma, \psi, \Delta\Omega) = \Phi_{\text{PP}}(E_\gamma) \times \Phi_{\text{cosmo}}(\psi, \Delta\Omega). \quad (1)$$

The particle physics factor is given by

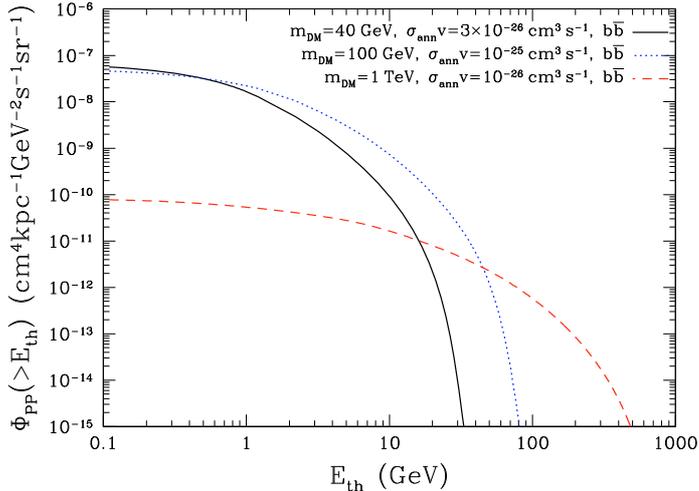
$$\Phi_{\text{PP}}(E_\gamma) = \frac{1}{4\pi} \frac{\sigma_{\text{ann}} v}{2m_{\text{DM}}^2} \sum_f B_f \int_{E_{\text{th}}} \frac{dN_\gamma^f}{dE_\gamma} dE, \quad (2)$$

where  $m_{\text{DM}}$  is the DM particle mass,  $\sigma_{\text{ann}}$  is the annihilation cross section, and  $v$  is the relative velocity.  $\sigma_{\text{ann}} v$  determines the number of annihilations.  $B_f$  is the branching ratio into a final state  $f$ . It represents the probability that the final state  $f$  is the result of one annihilation.  $dN_\gamma^f/dE_\gamma$  is the yield of photons produced by the final state  $f$  in one annihilation, and  $E_{\text{th}}$  is the threshold energy above which the flux is computed. So far no assumptions have been made on the nature of the DM particles. For a complete set of the allowed values for the previous parameters the reader is referred to [Fornengo et al. \(2004\)](#).

The astrophysical/cosmological factor is given by

$$\Phi_{\text{cosmo}}(\psi, \Delta\Omega) = \int \int_{\Delta\Omega} d\phi d\theta \int_{\text{LOS}} d\lambda \left[ \frac{\rho_{\text{DM}}^2(r)}{\lambda^2} J \right], \quad (3)$$

where  $\psi$  is the angle of view from the halo centre which defines the LOS and  $\Delta\Omega$  corresponds to the angular resolution of the instrument. It is a function of the photon energy,  $E_\gamma$ , although in



**Fig. 1.** Behaviour of  $\Phi_{pp}(>E_{th})$  as a function of  $E_{th}$  for different models of the DM particle, computed for a: 40 GeV (solid line), 100 GeV (dotted) and 1 TeV (dashed) DM particle annihilating into  $b\bar{b}$ . The value of  $\sigma_{ann}v$  has been chosen as representative of the best value for that mass, as computed with DARKSUSY and allowed by WMAP+SDSS measurements (see details in the text).

the following we will assume for simplicity  $\Delta\Omega = 10^{-5}$  sr (corresponding to a cone of view with angular opening of 0.1 degree along the LOS). This corresponds to the geometrical acceptance of the Fermi-LAT detector. Indeed, we made the simplifying assumption that the angular resolution of the Fermi-LAT is 0.1 degree over the entire energy range. This resolution is reached only for 10 GeV photons and for incidence angles less than  $50^\circ$ .  $\lambda$  is the coordinate along the LOS, and  $r$  the radial coordinate inside the halo.  $\rho_{DM}(r)$  is the DM mass density profile, which is a factor of primary importance when deriving the  $\gamma$ -ray flux from DM annihilation in a given source. Finally,  $J(x, y, z|\lambda, \theta, \phi)$  is the Jacobian determinant.

### 2.1. The particle physics factor

In Fig. 1 we draw the factor  $\Phi_{pp}$  integrated above a threshold energy  $E_{th}$  as a function of  $E_{th}$ . Shown in the plot is the result of the computation for a 40 GeV, 100 GeV and 1 TeV DM particle annihilating into quarks  $b\bar{b}$ . For the photon yields we have used the parametric formula from Fornengo et al. (2004) and introduced the pion bump feature at low energies. For each mass, we adopted the most optimistic value for  $\sigma_{ann}v$ , as computed with DARKSUSY (Gondolo et al. 2004) and allowed by WMAP+SDSS measurements (e.g., see Fig. 3 in Pieri et al. 2008). However, really few models lie in those very fortunate parts of the phase-space. In detail, we used  $\sigma_{ann}v = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$  for a 40 GeV DM particle,  $\sigma_{ann}v = 10^{-25} \text{ cm}^3 \text{ s}^{-1}$  for the 100 GeV particle case and  $\sigma_{ann}v = 10^{-26} \text{ cm}^3 \text{ s}^{-1}$  for the 1 TeV one.

Here we do not consider the result of Bringmann et al. (2008), who pointed out how previously ignored effects of electromagnetic radiative corrections to all leading annihilation processes in the Minimal Supersymmetric Model or in the Minimal SuperGRAvity mediated supersymmetry breaking scenarios can induce a  $\gamma$ -ray flux enhancement of up to three-four orders of magnitudes with respect to the  $\gamma$ -ray secondary flux produced in the annihilation cascade. This occurs when integrating over energies greater than 60% of  $m_{DM}$ , even for LSP masses well below the TeV scale. A careful study of the effect of internal

**Table 1.** The sample galaxies.

Object	$l$ deg	$b$ deg	Mass $M_\odot$	Distance kpc
Draco	86.37	34.77	$2.8 \times 10^7$	80
Ursa Minor	104.98	44.86	$1.3 \times 10^7$	66
Carina	260.09	-22.28	$1.3 \times 10^7$	87
Sextants	243.42	42.16	$1.9 \times 10^7$	80

Distances and masses are taken from Gilmore et al. (2007).

bremsstrahlung would be interesting for instruments with higher sensitivity at higher energies, such as Cherenkov telescopes (Bringmann et al. 2009), and is beyond the goal of this paper.

In the following, we will refer to a 40 GeV DM particle with  $\sigma_{ann}v = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ , annihilating into  $b\bar{b}$  as our best case scenario when studying the maximal  $\gamma$ -ray flux prediction integrated above 100 MeV. This is not the most likely model, and the real flux could be orders of magnitude smaller.

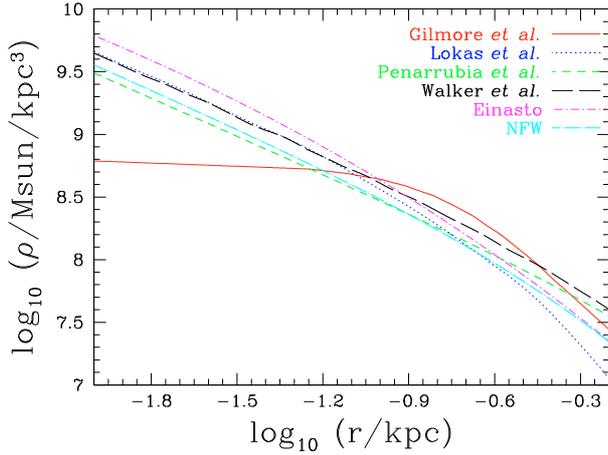
### 2.2. The astrophysical/cosmological factor

In this section we derive the value of  $\Phi_{cosmo}$  for four dSph galaxies of the Local Group both from the state-of-art DM density profiles available in literature and from CDM  $N$ -body simulations. Their positions, masses, and distances are reported in Table 1.

- **Draco:** Gilmore et al. (2007) calculated the DM density radial profile of the Draco dwarf galaxy. It was derived by Wilkinson et al. (2004) from the radial profiles of the velocity dispersion and surface brightness by solving the Jeans equations under the assumption of isotropic orbital structure. The velocity dispersion radial profile extends out to about 35 arcmin from the centre (corresponding to 0.8 kpc). It is characterized by an almost constant value of about  $13 \text{ km s}^{-1}$ , with a decrease to about  $5 \text{ km s}^{-1}$  at the last observed radius. The available data allowed to derive the mass density profile of the DM between about 0.1 and 0.5 kpc from the galaxy centre. The mass density increases out to the innermost observed point (Fig. 2).

Recently, an independent mass density profile for Draco has been obtained by Peñarrubia et al. (2008). They used the data by Wilkinson et al. (2004) and Muñoz et al. (2006) to reconstruct the mass distribution of the galaxy. They assumed that the galaxy is composed of a luminous component described by a King model (King 1966) and a DM component described by an NFW model. In this way they derived the concentration parameter of the DM halo component directly from a fit to the data, instead of assuming it from the CDM cosmology. A total mass of  $6.2 \times 10^9 M_\odot$  was found, which is somehow larger than expected for dSph galaxies (Mateo 1998). This DM density profile is shown in Fig. 2. The same procedure was applied to the other galaxies we analyze. Yet, as we will show in the following, this profile implies a more pessimistic  $\gamma$ -ray flux prediction. Since we are interested in the most optimistic scenarios that could lead to detection, we will consider the DM profiles derived by Peñarrubia et al. (2008) only in the case of Draco to derive the model uncertainty, while we will not consider it further for the other galaxies.

A third DM profile for Draco was obtained by Łokas et al. (2005). They used the data-set by Wilkinson et al. (2004) and assumed a Sérsic law (Sérsic 1968) to describe the



**Fig. 2.** The radial profile of the DM mass density in Draco as derived by Gilmore et al. (2007) (solid line), Lokas et al. (2005) (dotted), Walker et al. (2007) (long-dashed), and Peñarrubia et al. (2008) (dashed). Also shown are the density profiles derived from numerical simulations, namely the standard NFW (long-long-dashed) and the Einasto (long-dot-dashed) radial profiles.

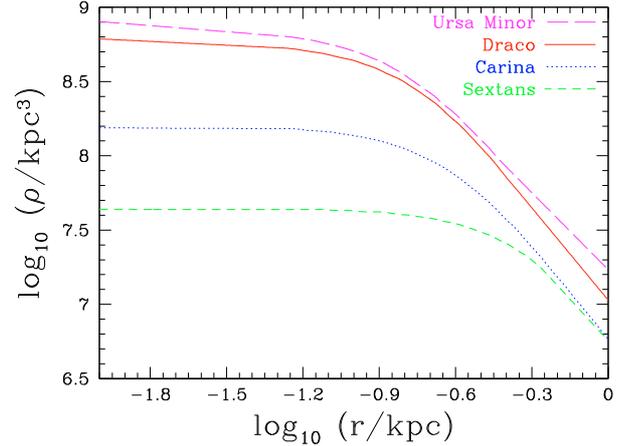
distribution of the luminous component. Concerning the DM density distribution, they assumed a modified NFW with an inner cusp and an exponential cut-off to take into account a possible tidal stripping in the outer regions of the galaxy. A tidal interaction does not affect the DM mass density profile in the centre, but produces a mass loss for radii larger than the so-called break radius (Kazantzidis et al. 2004). Lokas et al. (2005) break the degeneracy between the mass distribution and velocity anisotropy by fitting both the LOS velocity dispersion and kurtosis profiles. They found a total mass of  $7 \times 10^7 M_\odot$ . The corresponding radial profile of the DM mass density profile is shown in Fig. 2.

Finally, we show in Fig. 2 the density profile obtained by Walker et al. (2007) adopting a one-component King profile and an NFW profile with constant anisotropy parameter for the luminous and DM components, respectively.

A cored profile seems to be preferred for the DM mass density when no parametric function is imposed in fitting the data. A primordial density core would exclude a pure CDM scenario, rather pointing toward a warm dark matter particle. Yet, there are different studies about the possibility of dynamically removing the CDM cusp in the dwarf galaxies, involving phenomena such as stellar feedback (e.g., Mashchenko et al. 2006; Read & Gilmore 2005) or dynamical friction of DM/baryons subhaloes (Romano-Díaz et al. 2008). The topic is still controversial (see, e.g., Gnedin & Zhao 2002) and there is no univoque consensus about the realistic possibility that CDM cusps in dwarfs may be reduced to a core.

Given the lack of negative evidence we keep on using cored profiles associated with CDM particles in our discussion.

Although the main aim of the present paper is to present results based on density profiles directly inferred by astronomical data, it is worth superimposing on Fig. 2 the density profiles derived from numerical simulations. Stadel et al. (2008) have recently obtained from  $N$ -body simulations a best fit to a MW-sized halo which is a simple power law in  $d \log(\rho)/d \log(r)$  (called the Stadel & Moore profile, S&M). In the lack of halo mass scaling relations for the parameters of the S&M profile, we show only the NFW and



**Fig. 3.** The radial profile of the DM mass density in Ursa Minor (long-dashed line), Draco (solid line), Carina (dotted line), and Sextans (short-dashed line) as derived by Gilmore et al. (2007).

the Einasto profile computed for a  $10^9 M_\odot$  halo at a distance of 80 kpc, with the concentration parameter given by Kuhlen et al. (2008) ( $c = 20.2$ ,  $r_s = 1.02$  kpc,  $\rho_s^{\text{NFW}} = 3.56 \times 10^7 M_\odot \text{kpc}^{-3}$ ,  $\rho_s^{\text{Einasto}} = 8.9 \times 10^6 M_\odot \text{kpc}^{-3}$ ).

- **Ursa Minor:** the DM mass density profile for the Ursa Minor dwarf galaxy was taken from Gilmore et al. (2007). It was derived by Wilkinson et al. (2004) from the radial profiles of the velocity dispersion and surface brightness by solving the Jeans equations under the assumption of an isotropic orbital structure. The velocity dispersion radial profile extends out to 45 arcmin from the centre (corresponding to 0.9 kpc). It is characterized by a constant value of about  $12 \text{ km s}^{-1}$ , showing a sharp drop to about  $2 \text{ km s}^{-1}$  only at the farthest observed radius. The data allowed Gilmore et al. (2007) to derive the DM density distribution in the radial range between about 0.1 and 0.5 kpc. It is similar to that of Draco (Fig. 3).

Ursa Minor was also studied in Strigari et al. (2007), using the data by Palma et al. (2003). The light distribution was derived considering a two-component, spherically-symmetric King profile. They used the Jeans equations and adopted an NFW DM halo to derive the radial profile of the velocity dispersion fitting the data. The anisotropy parameter  $\beta$  was empirically set to the value of 0.6. In this paper we consider the two NFW models of the DM density profile given by Strigari et al. (2007): Model A has  $r_s = 0.63$  kpc and  $\rho_s = 10^8 M_\odot \text{kpc}^{-3}$ , Model B has  $r_s = 3.1$  kpc and  $\rho_s = 10^7 M_\odot \text{kpc}^{-3}$ .

- **Carina:** Gilmore et al. (2007) calculated the DM density radial profile of the Carina dwarf galaxy. It was derived from the radial profiles of the velocity dispersion and surface brightness by solving the Jeans equations under the assumption of isotropic orbital structure. The available measurements extend out to about the tidal radius of the galaxy, which corresponds to about 25 arcmin (corresponding to 0.6 kpc). The velocity dispersion is characterized by a constant value of about  $8 \text{ km s}^{-1}$ . The DM mass density profile is derived out to 60 pc from the centre and it shows a constant density core (Fig. 3).
- **Sextans:** the DM mass density profile for the Sextans dwarf galaxy was taken from Gilmore et al. (2007). It was derived by Wilkinson et al. (2006) from the radial profiles of the velocity dispersion and surface brightness measured by

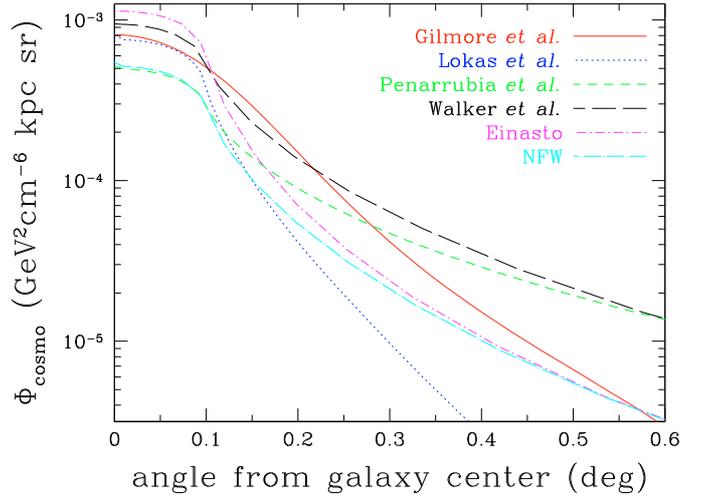
Kleyna et al. (2004) by solving the Jeans equations under the assumption of isotropic orbital structure. The velocity dispersion radial profile extends out to about 47 arcmin from the centre (corresponding to 1.1 kpc). It is characterized by a constant value of about  $8 \text{ km s}^{-1}$ , with a possible decrease to about  $3 \text{ km s}^{-1}$  at the last observed radius. The available data allowed Gilmore et al. (2007) to derive the mass density profile of the DM between about 0.2 and 0.8 kpc from the galaxy centre. It shows a constant density core (Fig. 3).

We would like to underline that the experimental results which we will use in our analysis give both cuspy and cored profiles. Although CDM simulations predict only cuspy haloes, we will keep on considering cored profiles and CDM particle because there may be mechanisms of gravitational heating of the dark matter by baryonic components which could reconcile observations of cored density profiles with the central density cusps of the CDM predictions.

Equation (3) has been integrated along the LOS adopting the DM density profiles we derived for each dSph galaxy. The result of this integration for the four different profiles inferred from the data as well as for the two profiles derived from numerical simulations for the Draco dSph galaxy is found in Fig. 4. The behaviour of these curves reflects the different DM distributions shown in Fig. 2. The fit to the data was obtained in the radial interval between 80 and 630 pc. The DM mass density profiles are extrapolated in the innermost and outermost galaxy regions. At large radii the DM mass density derived by Peñarrubia et al. (2008), who adopted an NFW density profile with no tidal disruption, is higher than that by Lokas et al. (2005) and Gilmore et al. (2007). Indeed, it is comparable to the result obtained by Walker et al. (2007), who also fit an NFW profile. Actually, the total mass derived by Peñarrubia et al. (2008) and Walker et al. (2007) is higher than the one typically found for this kind of galaxies (Mateo 1998). This behaviour reflects in the radial trend of the corresponding  $\Phi_{\text{cosmo}}$  (Fig. 4), which is higher at large radii with respect to those based on the results by Lokas et al. (2005) and Gilmore et al. (2007). The results based on the Walker et al. (2007) profile give a higher value of  $\Phi_{\text{cosmo}}$  in the inner galaxy than Peñarrubia et al. (2008), since the former predict a higher mass content at small radii (see Fig. 2).

The low DM mass density observed at large radii in the NFW profile of Lokas et al. (2005) is due to the mass stripping induced by a tidal interaction. Their DM density is higher in the centre, while the cored density profile by Gilmore et al. (2007) allocates more mass at intermediate radii (Fig. 2). Though biased by the different derived masses, this effect is due to mass conservation since the two models have about the same tidal radius. The DM mass density profile by Gilmore et al. (2007) gives a larger  $\Phi_{\text{cosmo}}$  for radii larger than 0.1 degree. At smaller radii it gives the same contribution as the DM mass density profile by Lokas et al. (2005, see Fig. 4). The Einasto profile, which predicts more mass at intermediate radii resolved by the angular resolution of 0.1 degrees, gives the highest value of  $\Phi_{\text{cosmo}}$ , while the NFW profile gives the same contribution as Peñarrubia et al. (2008). The values of the results for the NFW and Einasto profiles depend on the mass adopted for the computation. Here we have used  $10^9 M_{\odot}$  because the relative density profile was compatible with the amplitude of the profile inferred from the data.

The mass modeling of Draco produces only a difference of a factor of 2 to 3 in the flux predictions, while the indetermination arising from the unknown particle physics can add up to several orders of magnitude.



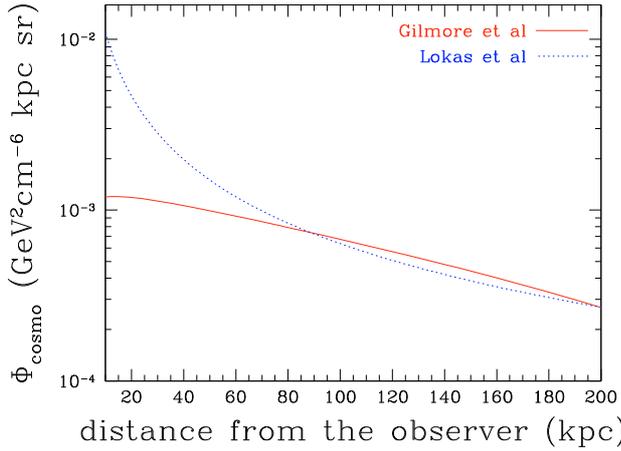
**Fig. 4.** The astrophysical/cosmological contribution  $\Phi_{\text{cosmo}}$  to the  $\gamma$ -ray flux derived as a function of the angular distance from the galaxy centre for Draco from the DM mass density radial profiles by Gilmore et al. (2007) (solid line), Lokas et al. (2005) (dotted), Walker et al. (2007) (long-dashed), and Peñarrubia et al. (2008) (dashed). Also shown are the results obtained from the density profiles derived from numerical simulations, namely the NFW standard (long-long-dashed) and the Einasto (long-dot-dashed) profiles.

To investigate the reason why, e.g., the cuspy profile by Lokas et al. (2005) and the cored profile by Gilmore et al. (2007) give the same value of  $\Phi_{\text{cosmo}}$  towards the centre of Draco, we considered a Draco-like dSph galaxy and changed its distance from the observer. We then computed  $\Phi_{\text{cosmo}}$  toward the centre of the galaxy. The result for the two profiles is plotted in Fig. 5 as a function of the imposed distance. The closer the galaxy, the greater the contribution to  $\Phi_{\text{cosmo}}$  due to the cuspy radial profile of the DM mass density. The geometrical acceptance of the Fermi-LAT detector is able to resolve the central cusp of the galaxy only if this is located at distances smaller than 90 kpc. Further out, the two profiles give more or less the same result. Curiously enough, the true location of the Draco dSph (80 kpc from us) lies exactly at the border of this region, so that we can conclude that no matter whether we choose either the cuspy DM profile by Lokas et al. (2005) or the cored profile by Gilmore et al. (2007), the estimate of the amount of  $\gamma$ -rays expected from DM annihilation in the central region of the galaxy will not change.

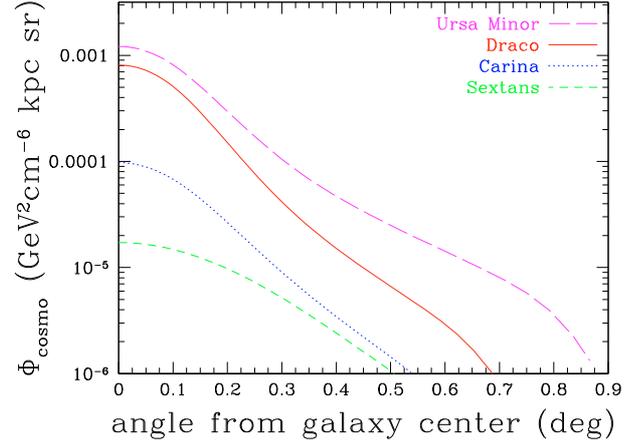
In Fig. 6 we plot the value of  $\Phi_{\text{cosmo}}$  for Ursa Minor for the cored Gilmore et al. (2007) profile, as well as for the cuspy Peñarrubia et al. (2008), and for the two fit to the NFW profile proposed in Strigari et al. (2007). As in the case of Draco, the Peñarrubia et al. (2008) profile gives the lowest value, while the two NFW models of Strigari et al. (2007) bracket the cored value at small angles.

What has been discussed above, also holds for the other dSph galaxies considered in this analysis. As an example, in Fig. 7 we plot the value of  $\Phi_{\text{cosmo}}$  obtained using the Gilmore et al. (2007) profile for the four dSph galaxies considered in this analysis. The values obtained using cuspy profiles will not deviate significantly from these values.

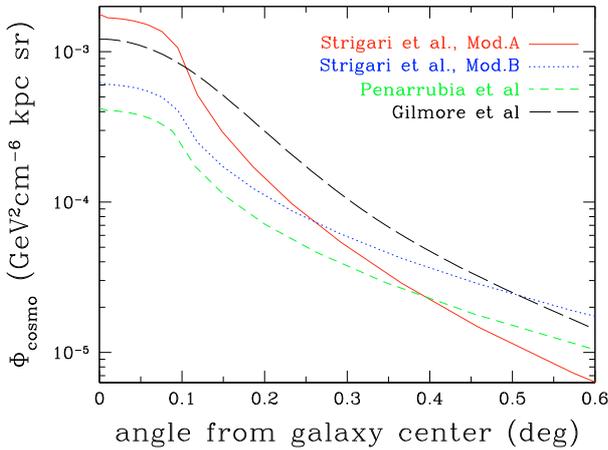
Figure 8 shows the values of  $\Phi_{\text{cosmo}}$  obtained the profiles by Gilmore et al. (2007) and computed for the LOS pointing toward the centre of the four dwarfs. These values are compared to the curve obtained for the smooth halo of the MW, obtained using Eq. (3), an angular resolution of 0.1 degrees and the NFW profile



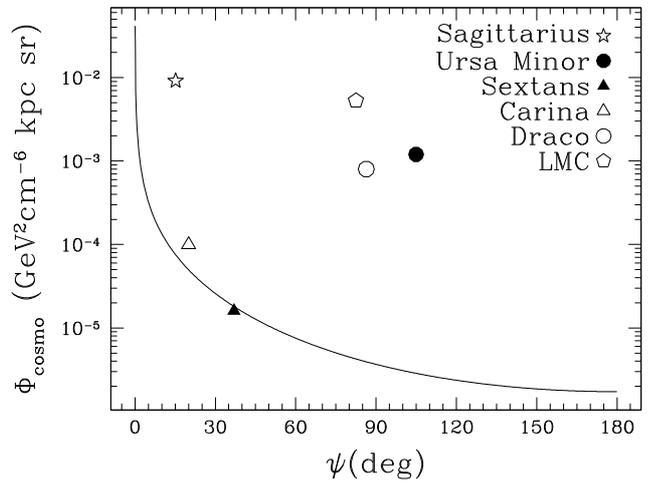
**Fig. 5.** The astrophysical/cosmological contribution  $\Phi_{\text{cosmo}}$  to the  $\gamma$ -ray flux computed in the centre of a Draco-like galaxy as a function of its distance to the observer. The DM was considered to be radially distributed as in Gilmore et al. (2007) (solid line) and Lokas et al. (2005) (dotted).



**Fig. 7.** The astrophysical/cosmological contribution  $\Phi_{\text{cosmo}}$  to the  $\gamma$ -ray flux derived as a function of the angular distance from the galaxy centre for Ursa Minor (long-dashed line), Draco (solid line), Carina (dotted line), and Sextans (short-dashed line) from the DM mass density radial profiles by Gilmore et al. (2007).



**Fig. 6.** The astrophysical/cosmological contribution  $\Phi_{\text{cosmo}}$  to the  $\gamma$ -ray flux derived as a function of the angular distance from the galaxy centre for Ursa Minor from the DM mass density radial profiles by Gilmore et al. (2007) (long-dashed line), Peñarrubia et al. (2008) (dashed), and for the two fit to the NFW profile proposed in Strigari et al. (2007) (solid and dotted).



**Fig. 8.** The astrophysical/cosmological contribution  $\Phi_{\text{cosmo}}$  to the  $\gamma$ -ray flux derived as a function of the angular distance from the center of the Milky Way centre, computed for a MW NFW smooth halo (solid curve), and for the central angular bin of Ursa Minor (filled circle), Draco (open circle), Carina (open triangle), and Sextans (filled triangle) derived using the DM mass density radial profiles by Gilmore et al. (2007). Also superimposed are the values for a NFW fit to the Sagittarius and the LMC galaxies.

for the MW ( $M_{\text{MW}} = 10^{12} M_{\odot}$ ,  $c = 7.55$ ,  $r_s = 27.3$  kpc). We observe that the dSph galaxies shine above the smooth Galactic halo at their position in the sky. Even more, we can say that Draco is brighter than the Galactic halo at all angles greater than 2.3 degrees above the Galactic center.

The central values of  $\Phi_{\text{cosmo}}$  for the Sagittarius dwarf galaxy and Large Magellanic Cloud (LMC) are shown in Fig. 8 for comparison with those of the other dSph galaxies we studied in detail. The Sagittarius dwarf galaxy is located at a distance of about 24 kpc. Although it is heavily interacting with the Milky Way, it has a surviving stellar component thus it is likely to have a surviving dark matter halo. The observations suggest that it is dark matter dominated with a central stellar velocity dispersion of about  $10 \text{ km s}^{-1}$  (Ibata et al. (1997)). According to recent observations and semi-analytic modelling (e.g. Strigari et al. 2008; Macció et al. 2008), the data consistent with all the DM halo of the dSph galaxies lie in the range between 20 and  $40 \text{ km s}^{-1}$ . We then modeled the inner regions of the DM halo of the Sagittarius

dwarf with the same scale parameters as Draco (see Evans et al. 2004) by assuming a NFW mass density profile and a mass of  $M = 10^9 M_{\odot}$ . The LMC is located at about 50 kpc. We adopted for its DM halo the stripped NFW profile used by Tasitsiomi et al. (2004) ( $M \sim 10^{10} M_{\odot}$ ).

### 3. Predictions for observation with the Fermi-LAT

The map of the Fermi-LAT sensitivity to point sources of DM annihilations has been obtained by Baltz et al. (2008) using the released Fermi-LAT response functions. The sensitivity map was obtained for 55 days of observation and it shows the minimum flux above 100 MeV which is necessary in order to achieve a  $5\sigma$  detection. The significance of the observed signal given the local background counts is assigned through a maximum likelihood analysis assuming Poisson statistics. Baltz et al. (2008) found that the sensitivity has very little dependence on the

underlying particle physics. Therefore, the obtained values can be considered valid as long as the source appears point-like in the sky, that is as long as its angular size does not exceed 0.25 degrees. As it can be seen in Fig. 7, the  $\gamma$ -ray flux expected from our dSph galaxies decreases by almost one order of magnitude at the angular distance of 0.25 degrees from the galaxy centre. For this reason, we can assume they are point-like sources and use the results of [Baltz et al. \(2008\)](#) for reference. Draco, Ursa Minor, and Sextans lie in a region of the sky where the  $5\sigma$  detection flux above 100 MeV is  $1.5 \times 10^{-8}$  ph cm $^{-2}$  s $^{-1}$  in  $\sim 2$  months. This translates into  $\phi_{5\sigma}^{1\text{ yr}} = 6 \times 10^{-9}$  ph cm $^{-2}$  s $^{-1}$  in 1 year of data taking and in the units we used throughout this paper. In the case of Carina, it is  $\phi_{5\sigma}^{1\text{ yr}} = 8 \times 10^{-9}$  ph cm $^{-2}$  s $^{-1}$ , since the galaxy is closer to the Galactic plane.

If we consider the best value for  $\Phi_{\text{pp}} (>100 \text{ MeV})$  from Fig. 1 ( $\Phi_{\text{pp}} \sim 6 \times 10^{-8}$  cm $^4$  kpc $^{-1}$  GeV $^{-2}$  s $^{-1}$  sr $^{-1}$ ) and the average value of  $\Phi_{\text{cosmo}}$  toward the galaxy centre ( $\psi = 0$ ) from Figs. 4 and 6, we end up with the following best-particle-physics-case estimates for the  $\gamma$ -ray flux from DM annihilation in Draco:

$$\Phi_{\gamma}^{\text{Draco}}(>100 \text{ MeV}) = (4.6 \pm 1.1) \times 10^{-11} \text{ ph cm}^{-2} \text{ s}^{-1} \quad (4)$$

and Ursa Minor:

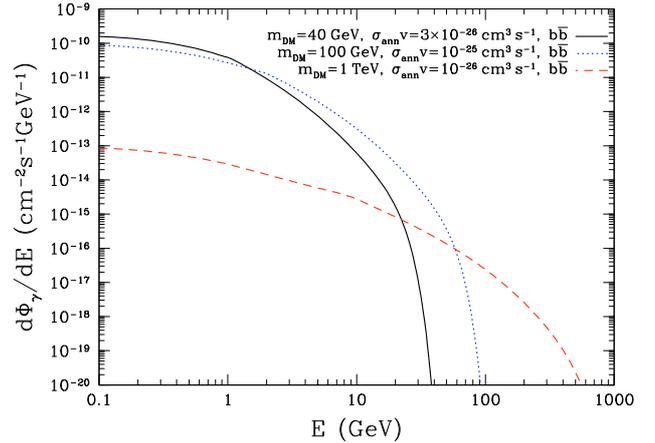
$$\Phi_{\gamma}^{\text{UMin}}(>100 \text{ MeV}) = (6.0 \pm 3.8) \times 10^{-11} \text{ ph cm}^{-2} \text{ s}^{-1}. \quad (5)$$

The error is given by the standard deviation for the values of  $\Phi_{\text{cosmo}}(\psi = 0)$  obtained using different DM density profiles inferred by dynamical modeling. We therefore do not focus on a specific profile when giving the value of the expected  $\gamma$ -ray flux. Indeed, our result is obtained by averaging over different fits to the data. Predictions made using profiles inferred from astronomical data are robust within a 60% relative error which is expected while changing the fit. This means that they can provide a reliable order-of-magnitude estimate of the real flux. We will not further consider the case of Carina and Sextans since they give a lower flux. However, the calculations of the expected  $\gamma$ -ray fluxes from DM annihilation in these galaxies are straightforward.

Even in the case of Draco and Ursa Minor the upper value of the predicted flux within the error is 2 orders of magnitude below that required for detection in 1 year of data taking with the Fermi-LAT ([Baltz et al. 2008](#)). This means that there is no hope of detection unless we allow for the presence of boost factors. Though brighter than the dSph considered in this analysis, nor the Sagittarius dwarf galaxy neither LMC have a predicted flux which could be detected with the Fermi-LAT.

In Fig. 9 we show the differential  $\gamma$ -ray fluxes expected from DM annihilation in the center of Ursa Minor for a 40 GeV, 100 GeV and 1 TeV DM particle annihilating into  $b\bar{b}$ . Fluxes are computed using the best value for  $\Phi_{\text{cosmo}}$  given by model A of [Strigari et al. \(2007\)](#). The values of  $\sigma_{\text{ann}}v$  have been chosen as in Fig. 1.

We note that if we use the same values for the annihilation cross-section and for the mass ( $\sigma_{\text{ann}}v = 5 \times 10^{-26}$  cm $^3$  s $^{-1}$ ,  $m_{\chi} = 46$  GeV) as in [Strigari et al. \(2007\)](#), as well as their model A for the density profile, we find a prediction for Ursa Minor which is  $\sim 10$  times smaller than their value. In fact, we get  $\Phi_{\gamma}(>5 \text{ GeV}) \sim 2.5 [5.4] \times 10^{-12}$  ph cm $^{-2}$  s $^{-1}$  for annihilation into  $b\bar{b}$  [ $\tau^+\tau^-$ ] to be compared with their value  $\Phi_{\gamma}(>5 \text{ GeV}) \sim 3 \times 10^{-11}$  ph cm $^{-2}$  s $^{-1}$ . This is due to the over-estimated number of photon yields above 5 GeV ( $\int_5^{m_{\chi}} dE dN_{\gamma}/dE_{\gamma} \sim 4.2$ ) which is derived in their paper. We found a number of photon yields which is an order of magnitude smaller both using the [Fornengo et al. \(2004\)](#) and the



**Fig. 9.** Differential  $\gamma$ -ray fluxes as a function of the energy expected from DM annihilation in the center of Ursa Minor. Fluxes are computed using the best value for  $\Phi_{\text{cosmo}}$  given by model A of [Strigari et al. \(2007\)](#), and are presented for a 40 GeV (solid line), 100 GeV (dotted) and 1 TeV (dashed) DM particle annihilating into  $b\bar{b}$ .

[Bergström et al. \(1998\)](#) parametrization for  $dN_{\gamma}/dE_{\gamma}$ , the latter being the one used by [Strigari et al. \(2007\)](#).

Investigating possible sources of astrophysical boost factors becomes necessary in order to understand the feasibility of a DM signal detection with the Fermi-LAT. To this purpose, in the following sections we account for the effect of the presence of clumps or of a SBH inside the dSph galaxies we are considering.

### 3.1. Boost factor due to the presence of dark matter clumps

According to the CDM scenario, each halo forms through the merging and accretion of smaller haloes, which still survive and orbit inside the larger one. The minimum mass of these subhaloes is  $\sim 10^{-6} M_{\odot}$  according to analytical estimates ([Green et al. 2004, 2005](#)). High-resolution  $N$ -body experiments, though they stop at high redshift ( $z = 26$ ), are able to resolve field haloes as small as  $\sim 10^{-6} M_{\odot}$ . Their mass function is well approximated by a power law

$$dn(M)/d\ln(M) \propto M^{-\alpha}, \quad (6)$$

with  $\alpha = 1$ , independently of the mass of the host halo, over the large redshift range between 0 and 75 and the mass interval between about  $10^{-6}$  and  $10^{10} M_{\odot}$  ([Diemand et al. 2005](#); [Giocoli et al. 2008](#)).

Assuming that the radial distribution of subhaloes traces that of the host galaxy, we can model the number density of subhaloes per unit mass at a distance  $R$  from the galaxy centre as

$$\rho_{\text{sh}}(M, R) = AM^{-2}\theta(R - r_{\text{min}}(M))\rho_{\text{gal}}(R) M_{\odot}^{-1} \text{ kpc}^{-3}, \quad (7)$$

where  $A$  is a normalization factor which takes into account the hypothesis that 10% of the Milky Way (MW) mass is distributed in substructures with masses in the mass range between  $10^7$  and  $10^{10} M_{\odot}$  ([Diemand et al. 2005](#)). The effect of tidal disruption is accounted for by the Heaviside step function  $\theta(r - r_{\text{min}}(M))$ , where the tidal radius  $r_{\text{min}}(M)$  is computed according to the Roche criterion as the minimum distance at which the subhalo self-gravity at its scale radius equals the gravity pull of the halo host computed at the orbital radius of the subhalo. The debate on the survival and partial disruption of these haloes is still open, and many issues are still unsolved, such as the true mass function after tidal interactions in the host halo and the inner structure and

concentration of the subhaloes themselves. See [Pieri et al. \(2008\)](#) for a detailed discussion of the problem.

Once we assumed a model for the subhalo population, the boost factor due to the presence of clumps distributed according to  $\rho_{\text{sh}}(M, r)$  is computed as the ratio of the integral over the galaxy volume of the density squared including subhaloes, to the same integral for the smooth galaxy only:

$$\text{BF}_{\text{SH}} = \frac{\int_{\text{gal}} dV \rho_{\text{gal,sm}}^2 + \int_{\text{gal}} \int_{M_{\text{sh}}} dV dM \rho_{\text{sh}} \int_{\text{halo}} dV \rho_{\text{h}}^2}{\int_{\text{gal}} dV \rho_{\text{gal,sm}}^2} \quad (8)$$

where  $\rho_{\text{gal,sm}}$  is the smooth profile of the DM component of the host halo which is not virialized into clumps and  $\rho_{\text{h}}$  is the internal DM density profile of each subhalo.

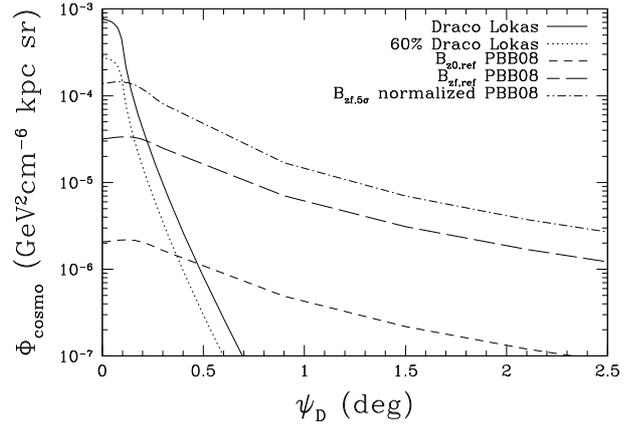
[Pieri et al. \(2008\)](#) found a relationship between the different subhalo models leading to various boost factors for the MW, the total number of photons produced at high galactic latitudes by the annihilation of DM particles in all the subhaloes falling into a given cone of view (of the order of  $10^9$ ), the EGRET measurement of the extragalactic  $\gamma$ -ray background (EGB), and the allowed particle physics contribution. They observed how a given model for the subhalo population cannot predict a number of photons greater than those observed by EGRET at high latitudes, where the  $\gamma$ -ray flux is thought to have a diffuse origin. Consequently, a maximum number of predictable photons exists. This means that the two factors  $\Phi_{\text{PP}}$  and  $\Phi_{\text{cosmo}}$  must be tuned in order not to exceed the EGRET limit. In the most optimistic case, they will be tuned so as to give exactly the number of photons observed by EGRET. This means that, if we assume a subhalo model for the MW, the value of  $\Phi_{\text{PP}}$  can be shifted down or up to match the EGRET level (up to the level of the best-particle-physics case of Fig. 1). Now, because of the lack of accurate models which account for the presence of subhaloes inside subhaloes, we make the simplifying assumption that the subhalo population of a dSph galaxy is described by the same subhalo model that we have assumed to be valid in the MW, so that the restrictions on  $\Phi_{\text{PP}}$  must still hold.

We have computed the boost factors in the cases of Draco and Ursa Minor, for all the subhalo models considered in [Pieri et al. \(2008\)](#), (PBB08 in Fig. 10) using Eq. (8). We found that the values for the boost factors range from 1.6 to 850, but when applying the corresponding limits on  $\Phi_{\text{PP}}$ , we end up, for any clump model, with an estimate of the maximum flux which may be produced by the clumps in Draco and Ursa Minor which is still compatible with the EGRET EGB and with the constraints given by particle physics shown in Fig. 1. The overall maximum enhancement of the flux obtained using Eq. (8), once scaled for the EGRET limit, is of a factor of 70.

The boost factor due to the presence of subhaloes has been computed analytically also in [Strigari et al. \(2007\)](#) and [Kuhlen et al. \(2008\)](#). The overall values are of the same order of magnitude as the one we obtain using the  $B_{z0,\text{ref}}$  model of [Pieri et al. \(2008\)](#). For that specific model, we obtain  $\text{BF}_{\text{SH}} = 2$ , which is not expected to give an enhancement of the  $\gamma$ -ray flux, which could be significant for detection.

The values of the boost factors obtained using Eq. (8), as well as those obtained analytically in [Strigari et al. \(2007\)](#) and [Kuhlen et al. \(2008\)](#), hold when integrating over all the galaxy. They are thus the numbers to consider when the galaxy is so far as to be pointlike inside the detector acceptance. This is indeed not the case for the nearby dwarfs considered in this analysis.

To understand what could really be the effect of sub-subhaloes in the closest dwarfs, we assumed an NFW profile for the substructures, defined by the concentration parameter  $c$



**Fig. 10.** The astrophysical/cosmological contribution  $\Phi_{\text{cosmo}}$  to the  $\gamma$ -ray flux as a function of the angular distance from the galaxy centre, derived for Draco using the DM mass density radial profiles by [Lokas et al. \(2005\)](#) (solid line). Dashed, dot-dashed and long-dashed lines show the contribution of all sub-subhaloes. The dotted line shows the contribution of the DM halo of Draco when only 60% of its mass is smoothly distributed in the halo.

distributed according to a log-normal probability  $P(c)$ , and computed their contribution to the annihilation signal as in [Pieri et al. \(2008\)](#):

$$\begin{aligned} \Phi^{\text{cosmo}}(\psi, \Delta\Omega) = & \int_M dM \int_c dc \int_{\Delta\Omega} d\theta d\phi \int_{1.0.s} d\lambda \\ & \times [\rho_{\text{sh}}(M, R(R_{\odot}, \lambda, \psi, \theta, \phi)) \times P(c) \\ & \times \Phi_{\text{halo}}^{\text{cosmo}}(M, c, r(\lambda, \lambda', \psi, \theta', \phi')) \times J(x, y, z|\lambda, \theta, \phi)] \quad (9) \end{aligned}$$

where  $\Delta\Omega$  is the solid angle of observation pointing in the direction of observation  $\psi$  and defined by the angular resolution of the detector  $\theta$ ;  $\rho_{\text{sh}}$  is the sub-subhaloes mass and distribution function inside the dwarf;  $J$  is the Jacobian determinant;  $R$  is the galactocentric distance,  $r$  is the radial coordinate inside the single sub-subhalo located at distance  $\lambda$  from the observer along the line of sight defined by  $\psi$  and contributing to the diffuse emission;  $\Phi_{\text{halo}}^{\text{cosmo}}$  describes the emission from each sub-subhalo. As in the case of the MW,  $\rho_{\text{sh}}$  is normalized such that 10% of the Draco mass is distributed in substructures with masses between  $10^{-5}$  and  $10^{-2} M_{\text{Draco}}$ . When integrating over all sub-subhaloes, we end up with 40% of the Draco mass distributed in  $10^{12}$  sub-subhaloes. The results of the computation of  $\Phi^{\text{cosmo}}$  using Eq. (9) are shown in Fig. 10 using different models for the concentration parameters, namely the  $B_{z0,\text{ref}}$ ,  $B_{z1,\text{ref}}$  and  $B_{z1,5\sigma}$  described in [Pieri et al. \(2008\)](#). Superimposed are the values of  $\Phi^{\text{cosmo}}$  for the profile by [Lokas et al. \(2005\)](#) with 100% and 60% of the mass of Draco smoothly distributed in the halo. The sum of the latter contribution and the sub-subhalo ones should be compared with the 100% smooth halo (solid line). We note that the effect of adding sub-substructures can give an enhancement of several orders of magnitude at large angles, where the overall flux is thought to be too low to be detected, even in the presence of sub-subhaloes. Yet, the effect in the very inner parts of the halo will be that of decreasing the expected signal, and the corresponding boost factor defined as  $(\Phi_{60\% \text{smooth}}^{\gamma} + \Phi_{\text{sub-subhaloes}}^{\gamma}) / \Phi_{100\% \text{smooth}}^{\gamma}$  is less than 1 where the greater detectable flux is expected, i.e. toward the galaxy center.

### 3.2. Boost factor due to the presence of a black hole

So far there are only two examples of dwarf galaxies suggested to host an SBH. Maccarone et al. (2005) discussed the possibility that the radio source near the core of the Ursa Minor dwarf galaxy is an SBH. They give a mass upper limit of  $\sim 10^4 M_\odot$ . Debattista et al. (2006) assumed that the double nucleus of the dE VCC 128 is a disk orbiting an SBH. They derived an SBH mass of  $\sim 10^7 M_\odot$ . The lack of SBHs in dwarf galaxies was explained by Ferrarese et al. (2006). They found that for galaxies less massive than a few  $10^9 M_\odot$  the formation of a compact stellar nucleus is more likely than that of an SBH. Both stellar nuclei and SBHs contain a mean fraction of about 0.2% of the total mass of the galaxy. The same conclusion was reached by Wehner & Harris (2006) and Côté et al. (2006).

Nevertheless, a value for the SBH mass of the dSph galaxies studied in this paper can be inferred using the  $M_{\text{SBH}} - \sigma$  relation (see Ferrarese & Ford 2005, for a review). Extrapolating the scaling law defined by SBHs in massive galaxies to the constant  $\sigma \approx 10 \text{ km s}^{-1}$  measured in the sample galaxies, the derived SBH mass is  $M_{\text{SBH}} \approx 10^2 M_\odot$ .

Gondolo & Silk (1999) and Merritt (2004) studied the effect of an adiabatically accreted SBH on a cuspy DM mass density profile [ $\rho(r) \propto r^{-\gamma}$  with  $0 < \gamma < 2$ ]. They found that the SBH induces a central density spike described by a power-law radial profile with index

$$\gamma_s = \frac{9 - 2\gamma}{4 - \gamma} \quad (10)$$

over a region of radius

$$r_s \approx 0.2 r_{\text{SBH}} = 0.2 \frac{GM_{\text{SBH}}}{\sigma^2} \quad (11)$$

where  $r_{\text{SBH}}$  is the radius of gravitational influence of a SBH with a mass  $M_{\text{SBH}}$  and  $\sigma$  is the DM velocity dispersion at  $r_{\text{SBH}}$ . Equation (10) reflects the condition of adiabaticity, requiring the SBH formation time to be much larger than the dynamical timescale at a distance  $r_{\text{SBH}}$ .

Assuming the cuspy DM mass density profile ( $\gamma = 1$ ) given by Łokas et al. (2005) for Draco, it results in

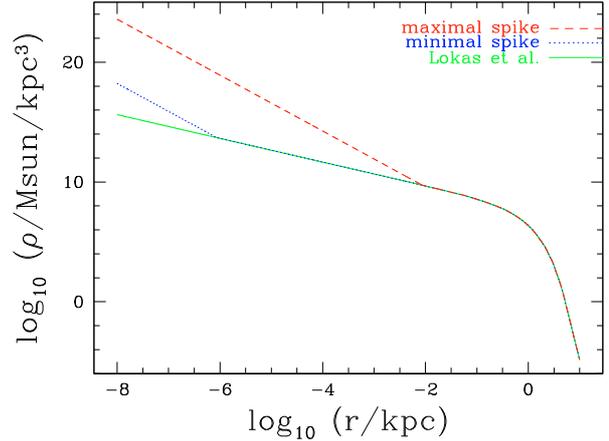
$$\rho_{\text{SBH+DM}}(r) = \begin{cases} \rho(r_c) & r \leq r_c \\ \rho(r_s) \left(\frac{r}{r_s}\right)^{-7/3} & r_c < r \leq r_s \\ \frac{M_{\text{DM}}}{4\pi r_b^2} \exp\left(-\frac{r}{r_b}\right) & r > r_s \end{cases} \quad (12)$$

where  $M_{\text{DM}}$  and  $r_b$  are the total DM mass and break radius as in Łokas et al. (2005), respectively. A core radius  $r_c = 10^{-8} \text{ kpc}$  was imposed to prevent the high annihilation rate which would destroy the spike. On the other hand, a mass density profile with constant-density core ( $\gamma = 0$ ) would not allow the growth of the spike. Therefore, it was not considered.

The effect of an SBH on the DM mass density profile by Łokas et al. (2005) is shown in Fig. 11 for two extreme values of  $r_s$ . For  $\sigma = 10 \text{ km s}^{-1}$ ,  $r_s = 10^{-3} \text{ pc}$  corresponds to  $M_{\text{SBH}} \approx 10^2 M_\odot$  and  $r_s = 10 \text{ pc}$  corresponds to  $M_{\text{SBH}} \approx 10^6 M_\odot$ . The adopted value of  $\sigma$  is consistent with the stellar velocity dispersion measured in the dSph galaxies we studied (Gilmore et al. 2007). It represents an upper limit for the DM velocity dispersion, since the stars are a tracer population of both the luminous and DM components.

The boost factor due to the presence of an SBH is

$$\text{BF}_{\text{SBH}} = \frac{\int_{\text{gal}} dV \rho_{\text{SBH+DM}}^2}{\int_{\text{gal}} dV \rho_{\text{gal,sm}}^2} \quad (13)$$



**Fig. 11.** The density spike induced by a SBH on the DM mass density profile of Draco. The initial profile is taken from Łokas et al. (2005) (solid line). The dotted and dashed lines correspond to a final density profile with a spike radius  $r_s = 10^{-3}$  and  $10 \text{ pc}$ , respectively.

Of course, a different parametrization of the SBH properties would result in different values of  $\text{BF}_{\text{BH}}$ . In particular, if we assume  $r_s = 10^{-3} - 10^{-2} \text{ pc}$  we end up with a boost factor in the range  $[1, 10]$ , while if we consider  $r_s = 1 - 10 \text{ pc}$  the boost factor becomes of the order of  $[5 \times 10^7, 10^9]$ .

A SBH mass  $M_{\text{SBH}} \approx 10^2 M_\odot$  results in  $r_s = 10^{-3} \text{ pc}$ , and in a boost factor equal to 1. On the other hand, Gilmore et al. (2007) reported that the existence of observed small stellar clumps inside Ursa Minor is not compatible with the presence of a spike, by which they would have been tidally destroyed.

The MAGIC collaboration recently published an upper limit on the  $\gamma$ -ray flux above  $140 \text{ GeV}$  for Draco at  $10^{-11} \text{ ph cm}^{-2} \text{ s}^{-1}$  (Albert et al. 2008). If we multiply the value of  $\Phi_{\text{cosmo}}$  in the direction of the centre of Draco by a boost factor  $\text{BF}_{\text{BH}} = 5 \times 10^7$  we end up with  $\Phi_{\text{cosmo}}|_{\text{BF}_{\text{BH}}} = 4 \times 10^4 \text{ GeV}^2 \text{ cm}^{-6} \text{ kpc sr}$ . This means that, if such a boost factor exists, either the DM particle mass is below  $140 \text{ GeV}$  and its annihilation products could not be observed with MAGIC, or that  $\Phi_{\text{pp}} < 2.5 \times 10^{-16} \text{ cm}^4 \text{ kpc}^{-1} \text{ GeV}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  which is a very low (though allowed) value.

## 4. Conclusions

The Fermi-LAT telescope was launched in June 2008 and is collecting data on  $\gamma$ -rays in the energy range between about  $20 \text{ MeV}$  and  $300 \text{ GeV}$ . Its all-sky survey operation mode will allow an unprecedentedly precise study of the  $\gamma$ -ray sky, so that many DM models will be tested. The dSph galaxies of the Local Group will be primary targets for DM analysis with the Fermi-LAT, because of the low astrophysical background expected in their direction. Therefore, we studied the detection limit of the  $\gamma$ -ray flux from DM annihilation in four of the nearest dSph galaxies, namely Draco, Ursa Minor, Carina, and Sextans.

State-of-the-art DM density profiles were available for these galaxies and we computed the expected  $\gamma$ -ray flux from DM annihilation for different particle physics parameters. We varied the DM particle mass as well as the annihilation cross-section and branching ratios. We found that the presence of an NFW-like cusp or constant density core in the DM mass density profile does not produce any relevant effect in the  $\gamma$ -ray flux due to a combination of the geometrical acceptance of the Fermi-LAT

detector, which is not able to resolve the very inner shells of the studied galaxies, and the distance of the sample galaxies.

In the case of Draco and Ursa Minor, we found that they would shine above the Galactic smooth halo for all but the smallest angles ( $\sim 2$  degrees) above the Galactic Center. Yet, the upper values of the predicted flux were found to be about two orders of magnitude below the Fermi-LAT detection threshold as derived in [Baltz et al. \(2008\)](#). Such values were computed for the most optimistic particle physics scenario of a 40 GeV particle with  $\sigma_{\text{ann}}v = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$  annihilating into  $b\bar{b}$ . We have shown how the effect of the boost factor due the presence of a population of DM clumps inside the dSph galaxies, though possibly very large (of the order of  $10^3$  when integrated over the whole galaxy), had to be rescaled for the limit on the EGB measured by EGRET. The overall maximal effect was reduced to a factor of 70. The calculation was made for a model where the subhalo population of the dwarf galaxies is described by the same model used for the MW. In any case, since the closest dwarfs are not pointlike for the Fermi-LAT angular acceptance  $\Delta\Omega$ , the factor to be taken into consideration is the effect of the sub-subhaloes inside  $\Delta\Omega$ , which resulted in a decrease of the expected flux due to a redistribution of the DM inside the halo. The presence of a central SBH in agreement with the  $M_{\text{SBH}} - \sigma$  relation extrapolated to the observed low  $\sigma$  values resulted in a negligible boost factor. More extreme models would result in a much higher boost factor, though they are not theoretically supported.

Contrarily to previous papers that addressed the presence of subhaloes or of SMBHs to boost the signal, we have demonstrated that the boost factor must be searched for in some exotic extension or modification of the particle physics. We conclude that, unless involved in this, the annihilation of DM inside the local dwarfs is unlikely to be detected with the Fermi-LAT.

As a further development, it will be interesting to repeat the present analysis of boost factors for the recently catalogued ultra faint dwarfs of the Local Group. [Strigari et al. \(2008\)](#) have computed the expected  $\gamma$ -ray flux from those sources, deriving the halo parameters from kinematic data. The inclusion of such galaxies in our study will improve the sensitivity of a joint multi-centred likelihood analysis.

Since the DM spectra would be the same for all the galaxies, such an analysis could be performed to maximise the detection efficiency and to allow portions of the particle physics phase-space to be explored.

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