Internal bremsstrahlung in neutralino annihilation: revised impact on indirect detection from $\gamma$-rays.

M. Cannoni$^1$, M. E. Gómez$^1$, M. A. Sánchez-Conde$^{2,3}$, F. Prada$^4$ and O. Panella$^5$

$^1$ Departamento de Física Aplicada, Facultad de Ciencias Experimentales, Universidad de Huelva, 21071 Huelva, Spain
$^2$ Instituto de Astrofísica de Canarias (IAC), E-38200 La Laguna, Tenerife, Spain
$^3$ Departamento de Astrofísica, Universidad de La Laguna (ULL), E-38205 La Laguna, Tenerife, Spain
$^4$ Instituto de Astrofísica de Andalucía (CSIC), E-18008, Granada, Spain
$^5$ Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Via Alessandro Pascoli, 06129, Perugia, Italy

E-mail: mirco.cannoni@dfa.uhu.es

Abstract. We revise the impact of internal bremsstrahlung photons in the context of the constrained minimal supersymmetric standard model on $\gamma$-ray dark matter annihilation searches. As an example, we review the $\gamma$-ray dark matter detection prospects from Draco dwarf spheroidal galaxy at the MAGIC stereoscopic system and the CTA project. We find that for a typical energy threshold of 100 GeV the flux of high energy photons is enhanced by an order of magnitude in the stau coannihilation region, where the signal remains still at least three orders of magnitude below the sensitivity of the instruments. However, the effect of internal bremsstrahlung is negligible or small in more optimistic scenarios for detection like the funnel and focus point regions.

1. $\gamma$-rays from neutralino annihilation

The detection of $\gamma$-rays coming from the annihilation of dark matter (DM) particles that should form the halo of galaxies is at present a very active field of research, which together with other indirect and direct search experiments [2], should give light to the nature of DM. The lightest neutralino of the minimal supersymmetric (SUSY) extension of the standard model (MSSM) is a natural candidate for dark matter (DM) [3]. There are three mechanisms producing photons in neutralino annihilation: (1) hadronization and decay of the annihilation products [4], mostly neutral pion decay, give secondary photons which show a continuous featureless energy spectrum decreasing towards $m_\chi$, the maximum energy available. Typically this is the largest contribution over a wide portion of the parameter space; (2) at the one loop level neutralinos annihilate into photons through the processes [5] $\chi\chi \rightarrow \gamma\gamma$ and $\chi\chi \rightarrow Z\gamma$. Being neutralino highly non relativistic, annihilation is almost at rest, thus outgoing photons are almost monochromatic (lines) with energies $E_\gamma \sim m_\chi$ and $E_\gamma \sim m_\chi - m_Z^2/4m_\chi$, respectively. Though this gammas would give a very clear signal the cross section is $\mathcal{O}(\alpha^4)$ and loop suppressed; (3) finally internal bremsstrahlung (IB) [6, 7] which consists the emission of additional photons in neutralino pair annihilation into charged final states $\chi\chi \rightarrow X\bar{X}\gamma X$ being a charged lepton or a $W$ boson. In the
Feynman diagrams these photons can be attached to the external legs representing final state charged particles or to the propagator of the virtual charged sparticle exchanged by neutralinos: the latter diagrams are at the origin of the hard photon spectrum of IB near \( m_\chi \). The cross section is \( \mathcal{O} (\alpha^3) \), thus in principle intermediate between the two previous contribution, but as we will see, strongly dependent on the SUSY mass spectrum.

The expected flux of photons with energy above an energy threshold set by experiments is given by \( F(E_\gamma > E_{\text{th}}) = J(\Psi) \times \Phi_{PP}(E_\gamma > E_{\text{th}}) \). Here \( J(\Psi) \) is the astrophysical factor and \( \Phi_{PP}(E_\gamma > E_{\text{th}}) \) is the particle physics factor that includes all the particle physics informations. Given the three sources discussed above, the particle physics factor that in the following we call \( f_{\text{susy}} \), explicitly reads

\[
\begin{align*}
  f_{\text{susy}} &= f_{\text{cont}} + f_{\text{lines}}, \\
  f_{\text{cont}} &= \left( \sum f \int_{E_{\text{th}}}^{m_\chi} \frac{dN_f}{dE_\gamma} \right) \frac{\langle \sigma_{\chi\chi} v \rangle}{2m_\chi^2} = f_{\text{sec}} + f_{\text{IB}}, \\
  f_{\text{lines}} &= 2 \frac{\langle \sigma_{\gamma\gamma} v \rangle}{2m_\chi^2} + \frac{\langle \sigma_{Z\gamma} v \rangle}{2m_\chi^2}.
\end{align*}
\]

Here \( dN_f / dE_\gamma \) is the differential yield of photons per annihilation to the final state \( f \). The factor in parenthesis is thus \( n_f(E_\gamma > E_{\text{th}}) \), the total number of photons per annihilation with energy greater than the threshold energy, \( \langle \sigma_{\chi\chi} v \rangle \) is the thermal averaged total neutralino annihilation cross, \( \langle \sigma_{\gamma\gamma} v \rangle \) and \( \langle \sigma_{Z\gamma} v \rangle \) the cross sections for annihilation into lines and \( m_\chi \) the neutralino mass.

For the numerical computation of IB effects we use DarkSusy 5.0.5 [8]. In the contest of the constrained minimal supersymmetric standard model (CMSSM) the theory at the weak scale is determined by four parameters assigned at the unification scale: the common scalar mass \( m_0 \), the gauginos mass \( m_{1/2} \), the trilinear couplings \( A_0 \), the ratio of the Higgs vacuum expectation values, \( \tan \beta \) and the sign of \( \mu \), the Higgs mixing term, that we take positive. We require the neutralino relic abundance to be inside the cosmologically favored interval \( 0 < \Omega_\chi h^2 < 0.13 \) (the most recent WMAP [9] interval at 3\( \sigma \) is 0.094 < \( \Omega_{DM} h^2 \) < 0.128). We further require that SUSY models satisfy the LEP bounds on Higgs and chargino masses, \( m_h > 114 \) GeV and \( m_{\chi^\pm} > 103.5 \) GeV, and constraints from \( b \to s \gamma \) as explained in Refs. [10].

After the imposition of the phenomenological constraints only few regions of the parameter space survive (see [11] for review). In these regions the relative weight of the three contributions to \( f_{\text{susy}} \) and to the flux changes drastically: to illustrate this behavior we select from our scan of the parameter space four points found in Table 1 where also the annihilation cross section and the distinct contributions to \( f_{\text{susy}} \) integrating the number of photons above \( E_{\text{th}} = 100 \) GeV can be read. The corresponding differential spectra of photons are shown in Fig. 1.

Point (A) is in the \emph{stau coannihilation region} of the CMSSM parameter space: the mass of the lightest stau is \( m_{\tilde{\tau}} = 195 \) GeV very close to \( m_\chi = 188 \) GeV. Neutralino pair annihilation in \( \tau^+ \tau^- \) mediated by \( t \)-channel exchange of stau has the highest annihilation cross section. Here \( f_{\text{IB}} \) is the dominant contribution being 10 and 4.4 times greater than \( f_{\text{sec}} \) and \( f_{\text{lines}} \).

Point (B) is in the \emph{funnel or resonances region}: the mass of the CP-odd neutral Higgs is \( m_A = 1211 \) GeV while \( m_{\chi^0} = 598 \) GeV, thus \( m_A \approx 2m_{\chi^0} \); pair annihilation into \( bb \) through \( s \)-channel exchange of heavy neutral Higgs bosons is the dominant channel. In this case no photon line can be attached to the virtual particles in \( t \) channel exchange and the IB yield is negligible. \( f_{\text{sec}} \) is the only relevant contribution.

Point (C) is in the \emph{focus point or hyperbolic branch region}: the mass of the lightest chargino is \( m_{\chi^\pm} = 212 \) GeV, not much bigger than \( m_\chi = 163 \) GeV and neutralino pairs annihilate into \( W^+ W^- \) through \( t \)-channel chargino exchange. The IB yield is small because \( m_\chi \) is not much
greater than $m_W$ and photons energy has a cut off which corresponds to the kinematic endpoint $x = 1 - m_W^2/m_{\chi}^2 \sim 0.75$. Here $f_{\text{lines}}$ is bigger than $f_{\text{sec}}$ and $f_{\text{IB}}$, and the three contribution are of the same order.

Point (D) is another example in the focus point region. The mass of the lightest chargino is $m_{\chi} = 954$ GeV, almost degenerate with $m_{\chi} = 918$ GeV. Neutralino pairs annihilate into $W^+W^-$ through $t$-channel chargino exchange as in C but in this case $m_{\chi} \gg m_W$ thus IB photons contribution is more important and have endpoint at the neutralino mass: here $f_{\text{SUSY}}$ is dominated by $f_{\text{sec}}$ even if $f_{\text{IB}}$ is greater than $f_{\text{lines}}$.

Note that although $f_{\text{IB}}$ can be dominant, point (A), or bigger or of the same order of $f_{\text{lines}}$, points (D) and (C), the bigger $f_{\text{sec}}$ is reached in point (B) where $f_{\text{IB}}$ is irrelevant, thus from the point of view of the most promising scenario for detection there is no improvement: we discuss this point in a more general way in Section 3.

2. Astrophysical target: Draco dwarf galaxy
Gamma rays are detected by imaging air Cerenkov telescopes (IACT) like MAGIC [11], HESS [12], VERITAS [13] or satellites-based experiments like the FERMI satellite [14]. For these experiments, dwarf spheroidal (dSph) galaxies around the Milky Way represent a good

---

**Table 1.** CMSSM used in Fig. 1. The values of $m_0$, $m_{1/2}$, $A_0$, $m_{\tilde{\chi}}$ are in GeV, the sign of $\mu$ is positive. $(\sigma v)$ is given in units of $10^{-29}$ cm$^3$ s$^{-1}$, the $f$’s, defined in Eq. (1), are given in units of $10^{-32}$ GeV$^{-2}$ cm$^3$ s$^{-1}$.

| Model | $\tan \beta$ | $m_0$ | $m_{1/2}$ | $A_0$ | $(\sigma v)$ | $f_{\text{sec}}$ | $f_{\text{lines}}$ | $f_{\text{IB}}$ | $f_{\text{SUSY}}$ |
|-------|--------------|--------|----------|------|------------|----------------|----------------|-------------|-------------|
| (A)   | 18           | 127    | 459      | $-135$ | 29         | 0.008          | 0.018          | 0.079       | 0.1         |
| (B)   | 52           | 982    | 1377     | 725   | 2600       | 0.72           | $10^{-5}$      | $10^{-5}$   | 0.72        |
| (C)   | 17           | 2200   | 430      | 805   | 2225       | 0.04           | 0.06           | 0.02        | 0.12        |
| (D)   | 51           | 8940   | 2218     | $-4221$ | 1203       | 0.3            | 0.003          | 0.017       | 0.32        |
alternative target option to e.g. the Galactic Center [15], already observed in γ-rays but with null DM detection so far [16]. dSphs are DM dominated systems with inferred very high mass-to-light ratios, and most of them are expected to be free from any other astrophysical source that might contribute to a possible γ-ray signal. Therefore, the detection of γ-rays from them would probably imply a successful DM annihilation detection. Here we consider Draco, located at 80 kpc, is one of the dwarfs with more observational constraints, which have helped to better determine its DM density profile and is one of the most studied dSph [17] [18]. Draco has already been observed by some of the quoted experiments:

The MAGIC telescope [19], found no gamma signal above an energy threshold of 140 GeV. As a consequence, an upper limit for the flux (2σ level) was set to be $1.1 \times 10^{-11}$ photons cm$^{-2}$ s$^{-1}$, assuming a power-law with spectral index $-1.5$ and a point-like source. This upper limit is $O(10^3 - 10^9)$ above the values predicted by those SUSY models used in their analysis and therefore no constraints could be put on the parameter space. The FERMI collaboration has reported their upper limits for a possible γ-ray annihilation signal from Draco at lower energies [20], given that no significant gamma emission was detected above 100 MeV (see also A. Morselli contribution to these proceedings). Recently also the VERITAS collaboration [21] has published results of 18.38 hours of observation of Draco: finding no signal an upper limit at 95% on the total flux was set to be $0.49 \times 10^{-12}$ photons cm$^{-2}$ s$^{-1}$ above 200 GeV.

The astrophysical factor $J(\Psi)$ represents the integral of the square of the dark matter density $\rho_{DM}$ along the direction of observation $\Psi$ relative to the center of the DM halo, and depends on the point spread function of the telescope (PSF). In the case of Draco we use the cuspy DM density profile given in Refs. [22]-[1] also used by the MAGIC collaboration in their analysis [11]. In particular we use here the value of $J(\Psi)$ integrated over the whole spatial extent of the source as the value of the astrophysical factor. This value, that does not depend on the PSF any longer, can be well approximated by $\mathcal{J} = \frac{1}{4\pi D^2} \int_V \rho_{DM}^2(r) \, dV$, with $D$ the distance from the Earth to the center of the DM halo and $r$ the galactocentric distance inside it: for Draco we take a value of $\mathcal{J} = 3.7 \times 10^{17}$ Gev$^2$ cm$^{-5}$. We remark that in literature others models for the halo profiles are used providing slightly different values for $J$: in particular both FERMI and VERITAS analysis are assume a two parameters Navarro-Frank-White profile [23]. As noted also in Ref. [18] the uncertainties on the astrophysical factor are of order of a factor 2-3 using different models: this uncertainty is however irrelevant with the present experimental sensitivity as we show in the next section.

3. Results

Armed with the previous ingredients we perform a scan on the parameter space of $f_{SUSY}$ versus the threshold energy, which is the important quantity determining the flux once the astrophysical factor is fixed. We set $A_0 = 0$ and take two values of $\tan \beta$, 10 and 50 varying $m_0$ and $m_{1/2}$ such that the experimental constraints discussed in Section 1 are satisfied. For each value of $\tan \beta$ we separate the models with $m_0 > 2$ TeV and $m_0 < 2$ TeV in order to separate the focus point region from the stau coannihilation and the Higgs funnel ones. In Fig. 2 the shaded areas correspond to the total $f_{SUSY}$, the areas inside the dot-dashed lines correspond to $f_{sec}$ and the areas inside the dashed lines give $f_{lines}$.

In panel (a) of Fig. 2 where points are in the stau coannihilation region we can appreciate the largest contribution of IB, as shown by the point (A). The absence of IB photons of the point (B) is evidenced by the panel (b) where points are in the funnel region, while the panels (c) and (d) have points mostly in the hyperbolic branch and share properties with the points (C) and (D).

To compare we the future experimental sensitivities we plot in these panels the sensitivity lines for Draco of the MAGIC telescopes in stereoscopic mode [24] and of the CTA project [25]. These lines are obtained dividing the Montecarlo simulated sensitivity for the flux (50 hours of
Let us focus at $E_{th} = 100$ GeV, the typical energy threshold for the telescopes. The IB contribution is seen to be important only in panel (a) corresponding to the stau coannihilation region, as expected. The order of magnitude effect has the net result of pushing $f_{SUSY}$ to the value $\approx 10^{-33}$ GeV$^{-2}$ cm$^2$ s$^{-1}$ as in panel (b): but this value is smaller than the value reached in panel (c) and (d), $f_{SUSY} \approx 5 \times 10^{-33}$ GeV$^{-2}$ cm$^2$ s$^{-1}$ that is the most optimistic value. Thus we see that if from one side IB rises by an order of magnitude the flux in the stau coannihilation region, on the other side the sensitivity of the experiments to this region is more than three order of magnitude far away, that is the worst case scenario for $\gamma$-rays scenario remain the worst case. Note that the same is true at low threshold, say 1 GeV of interest for FERMI satellite, where $f_{SUSY}$ is three orders of magnitude smaller than in panels (b), (c), (d).

### 4. Summary

Although IB has to be included for evaluation of fluxes of high energy photons from neutralino annihilation, its contribution is relevant only in the stau coannihilation region of the CMSSM parameter space: as a result, the most optimistic particle physics scenarios for DM detection, which typically correspond to those points of the parameter space where most of the flux is given by secondary photons, will not change substantially. As an example of the impact of the IB on DM search, we recalcualted the DM detection prospects of the Draco dwarf galaxy for the MAGIC II and the future CTA telescopes: though the effect can rise the flux in the observation time and a $5\sigma$ detection level) by the total astrophysical factor discussed in Section 2.

Let us focus at $E_{th} = 100$ GeV, the typical energy threshold for the telescopes. The IB contribution is seen to be important only in panel (a) corresponding to the stau coannihilation region, as expected. The order of magnitude effect has the net result of pushing $f_{SUSY}$ to the value $\approx 10^{-33}$ GeV$^{-2}$ cm$^2$ s$^{-1}$ as in panel (b): but this value is smaller than the value reached in panel (c) and (d), $f_{SUSY} \approx 5 \times 10^{-33}$ GeV$^{-2}$ cm$^2$ s$^{-1}$ that is the most optimistic value. Thus we see that if from one side IB rises by an order of magnitude the flux in the stau coannihilation region, on the other side the sensitivity of the experiments to this region is more than three order of magnitude far away, that is the worst case scenario for $\gamma$-rays scenario remain the worst case. Note that the same is true at low threshold, say 1 GeV of interest for FERMI satellite, where $f_{SUSY}$ is three orders of magnitude smaller than in panels (b), (c), (d).
stau coannihilation region by an order of magnitude at $E_{\text{th}} = 100$ GeV, the predicted fluxes are still at least three orders of magnitude below the sensitivity of the IACTs, and the most optimistic scenario for detection are found in the funnel and focus point regions where internal bremsstrahlung is negligible or small.

Acknowledgments

M. C. acknowledges D. Delepine and all the members of the local organizing committee for the warm hospitality in Leon during the workshop. The authors acknowledges support from the project P07-FQM02962 funded by “Junta de Andalucia”, the Spanish MICINN-INFN(PG21) projects FPA2009-10773, FPA2008-04063-E and MULTIDARK project of Spanish MICINN Consolider-Ingenio: CSD2009-00064.

References

[1] Cannoni M, Gomez M E, Sanchez-Conde M A, Prada F and Panella O 2010 Phys. Rev. D 81, 107303
[2] Munoz C 2004 Int. J. Mod. Phys. A 19 3093
[3] Jungman G, Kamionkowski M and Griest K 1996 Phys. Rept. 267 195; Bertone G, Hooper D and Silk J 2005 Phys. Rept. 405 279
[4] Silk J and Srednicki M 1984 Phys. Rev. Lett. 53 624
[5] Bergstrom L and Ullio P 1997 Nucl. Phys. B 504 27; Bern Z, Gondolo P and Perelstein M 1997 Phys. Lett. B 411 86; Ullio P and Bergstrom L 1998 Phys. Rev. D 57 1962
[6] Bergstrom L 1989 Phys. Lett. B 225 372; Flores R, Olive K A and Rudaz S 1989 Phys. Lett. B 232 377; Bergstrom L, Bringmann T, Eriksson M and Gustafsson M 2005 Phys. Rev. Lett. 95 241301
[7] Bringmann T, Bergstrom L and Edsjo J 2008 J. High Energy Phys. JHEP01(2008)049
[8] Gondolo P, Edsjo J, Ullio P, Bergstrom L, Schelke M and Baltz E A 2004 J. Cosmol. Astropart. Phys. JCAP07(2004)008
[9] Larson D et al. 2011 Astrophys. J. Suppl. 192 16
[10] Gomez M E, Ibrahim T, Nath P and Skadhauge S, 2005 Phys. Rev. D 72 095008; 2006 ibid. 74, 015015; Gomez M E, Lazarides G and Pallis C 2002 Nucl. Phys. B 638 165; 2003 Phys. Rev. D 67 097701; Cannoni M and Panella O 2010 Phys. Rev. D 81 036009
[11] Lorenz E 2004 New Astron. Rev. 48 339
[12] Hinton J A 2004 New Astron. Rev. 48 331
[13] Weekes T C et al. 2002 Astropart. Phys. 17 221
[14] Gehrels N and Michelson P 1999 Astropart. Phys. 11 277
[15] Bergstrom L, Ullio P and Buckley J H 1998 Astropart. Phys. 9 137; Cesaroni A, Fucito F, Lionetto A, Morselli A and Ullio P 2004 Astropart. Phys. 21 267; Fornengo N, Pieri L and Scopel S 2004 Phys. Rev. D 70, 103529
[16] Aharonian F et al. 2004 Astron. Astrophys. 425 L13; Albert J et al. 2006 Astrophys. J. 638 L101 Aharonian J et al. 2006 Phys. Rev. Lett. 97 221102
[17] Tyler C 2002 Phys. Rev. D 66 023509; Bergstrom L and Hooper D 2006 Phys. Rev. D 73 063510; Profumo S and Kamionkowski M 2006, J Cosmol. Astrop. Phys JCAP03(0603)003; Colafrancesco S, Profumo S and Ullio P 2007 Phys. Rev. D 75 023513; Strigari L E, Kousshiappas S M, Bullock J S and Kaplinghat M 2007 Phys. Rev. D 75 083526
[18] Bringmann T, Doro M and Fornasa M 2009 J. Cosmol. Astropart. Phys. JCAP01(0901) 016
[19] Albert J et al. 2008 Astrophys. J. 679 428
[20] Abdo A A et al. 2010 Astrophys. J. 712 147
[21] Acciari V A et al. 2010 Astrophys. J. 720 1174
[22] Sanchez-Conde M A, Prada F, Lokas E L, Gomez M E, Wojtak R and Mores M 2007 Phys. Rev. D 76 123509
[23] Navarro J F, Frenk C S and White S D M 1997 Astrophys. J. 490 493
[24] P, Colin et al. 2009 Performance of the MAGIC telescopes in stereoscopic mode Preprint 0907.0960
[25] Doro M 2011 Nucl. Instrum. Meth. A 630 285