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Results from the search for dark matter in the Milky Way with 9 years of data of the ANTARES neutrino telescope

A. Albert[a], M. André[b], M. Anghinolfi[c], G. Anton[d], M. Ardid[e], J.-J. Aubert[f], T. Avgitas[g], B. Baret[g], J. Barrios-Martí[h], S. Basa[i], V. Bertin[f], S. Biagi[j], R. Bormuth[k,l], S. Bourret[g], M.C. Bouwhuis[k], R. Bruijn[k,m], J. Brunner[f], J. Busto[f], A. Capone[n,o], L. Caramete[p], J. Carr[f], S. Celli[n,o,q], T. Chiarusi[r], M. Circella[s], J.A.B. Coelho[g], A. Coleiro[g], R. Coniglione[j], H. Costantini[f], P. Coyle[f], A. Creusot[g], A. Deschamps[t], G. De Bonis[n,o], C. Distefano[j], I. Di Palma[n,o], C. Donzaud[g,u], D. Dornic[f], D. Drouhin[a], T. Eberl[d], I. El Bojaddaini[v], D. Elsässer[w], A. Enzenhöfer[f], I. Felis[e], L.A. Fusco[r,x], S. Galatà[g], P. Gay[y,g], S. Geißelsöder[d], K. Geyer[d], V. Giordano[z], A. Gleixner[d], H. Glotin[aa,ab,ac], T. Grégoire[g], R. Gracia Ruiz[g], K. Graf[d], S. Hallmann[d], H. van Haren[ad], A.J. Heijboer[k], Y. Hello[t], J.J. Hernández-Rey[h], J. Hößl[d], J. Hofestädt[d], C. Hugon[c,ae], G. Illuminati[n,o,h], C.W. James[d], M. de Jong[k,l], M. Jongen[k], M. Kadler[w], O. Kalekin[d], U. Katz[d], D. Kießling[d], A. Kouchner[g,ac], M. Kreter[w], I. Kreykenbohm[af], V. Kulikovskiy[f,ag], C. Lachaud[g], R. Lahmann[d], D. Lefèvre[ah,ai], E. Leonora[z,aj], M. Lotze[h], S. Loucatos[ak,g], M. Marcelin[i], A. Margiotta[r,x], A. Marinelli[al,am], J.A. Martínez-Mora[e], A. Mathieu[f], R. Mele[an,aq], K. Melis[k,m], T. Michael[k], P. Migliozzi[an], A. Moussa[v], C. Mueller[w], E. Nezri[i], G.E. Păvălaş[p], C. Pellegrino[r,x], C. Perrina[n,o], P. Piattelli[j], V. Popa[p], T. Pradier[ao], L. Quinn[f], C. Racca[a], G. Riccobene[j], K. Roensch[d], A. Sánchez-Losa[s], M. Saldaña[e], I. Salvadori[f], D.F.E. Samtleben[k,l], M. Sanguineti[c,ae], P. Sapienza[j], J. Schnabel[d], F. Schüssler[ak], T. Seitz[d], C. Sieger[d], M. Spurio[r,x], Th. Stolarczyk[ak], M. Taiuti[c,ae], Y. Tayalati[ap], A. Trovato[j], M. Tselengidou[d], D. Turpin[f], C. Tönnis[h,*], B. Vallage[ak,g], C. Vallée[f], V. Van Elewyck[g,ac], D. Vivolo[an,aq], A. Vizzoca[n,o], S. Wagner[d], J. Wilms[af], J.D. Zornoza[h], J. Zúñiga[h]

[a] GRPHE, Université de Haute Alsace, Institut universitaire de technologie de Colmar, 34 rue du Grillenbreit, BP 50568, 68008 Colmar, France
[b] Technical University of Catalonia, Laboratory of Applied Bioacoustics, Rambla Exposició, 08800 Vilanova i la Geltrú, Barcelona, Spain
[c] INFN – Sezione di Genova, Via Dodecaneso 33, 16146 Genova, Italy
[d] Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics, Erwin-Rommel-Str. 1, 91058 Erlangen, Germany
[e] Institut d'Investigació per a la Gestió Integrada de les Zones Costaneres (IGIC), Universitat Politècnica de València, C/ Paranimf 1, 46730 Gandia, Spain
[f] Aix-Marseille Université, CNRS/IN2P3, CPPM UMR 7346, 13288 Marseille, France
[g] APC, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 75205 Paris, France
[h] IFIC – Instituto de Física Corpuscular (CSIC – Universitat de València), c/ Catedrático José Beltrán, 2, E-46980 Paterna, Valencia, Spain
[i] LAM – Laboratoire d'Astrophysique de Marseille, Pôle de l'Étoile Site de Château-Gombert, rue Frédéric Joliot-Curie 38, 13388 Marseille Cedex 13, France
[j] INFN – Laboratori Nazionali del Sud (LNS), Via S. Sofia 62, 95123 Catania, Italy
[k] Nikhef, Science Park, Amsterdam, The Netherlands
[l] Huygens-Kamerlingh Onnes Laboratorium, Universiteit Leiden, The Netherlands
[m] Universiteit van Amsterdam, Instituut voor Hoge-Energie Fysica, Science Park 105, 1098 XG Amsterdam, The Netherlands
[n] INFN – Sezione di Roma, P.le Aldo Moro 2, 00185 Roma, Italy
[o] Dipartimento di Fisica dell'Università La Sapienza, P.le Aldo Moro 2, 00185 Roma, Italy
[p] Institute for Space Science, RO-077125 Bucharest, Măgurele, Romania
[q] Gran Sasso Science Institute, Viale Francesco Crispi 7, 00167 L'Aquila, Italy
[r] INFN – Sezione di Bologna, Viale Berti-Pichat 6/2, 40127 Bologna, Italy
[s] INFN – Sezione di Bari, Via E. Orabona 4, 70126 Bari, Italy
[t] Géoazur, UCA, CNRS, IRD, Observatoire de la Côte d'Azur, Sophia Antipolis, France
[u] Univ. Paris-Sud, 91405 Orsay Cedex, France
[v] University Mohammed I, Laboratory of Physics of Matter and Radiations, B.P. 717, Oujda 6000, Morocco
[w] Institut für Theoretische Physik und Astrophysik, Universität Würzburg, Emil-Fischer Str. 31, 97074 Würzburg, Germany
[x] Dipartimento di Fisica e Astronomia dell'Università, Viale Berti Pichat 6/2, 40127 Bologna, Italy
[y] Laboratoire de Physique Corpusculaire, Clermont Univertsité, Université Blaise Pascal, CNRS/IN2P3, BP 10448, F-63000 Clermont-Ferrand, France

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[z] INFN – Sezione di Catania, Viale Andrea Doria 6, 95125 Catania, Italy
[aa] LSIS, Aix Marseille Université, CNRS, ENSAM, LSIS UMR 7296, 13397 Marseille, France
[ab] Université de Toulon, CNRS, LSIS UMR 7296, 83957 La Garde, France
[ac] Institut Universitaire de France, 75005 Paris, France
[ad] Royal Netherlands Institute for Sea Research (NIOZ), Landsdiep 4, 1797 SZ 't Horntje (Texel), The Netherlands
[ae] Dipartimento di Fisica dell'Università, Via Dodecaneso 33, 16146 Genova, Italy
[af] Dr. Remeis-Sternwarte and ECAP, Universität Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany
[ag] Moscow State University, Skobeltsyn Institute of Nuclear Physics, Leninskie gory, 119991 Moscow, Russia
[ah] Mediterranean Institute of Oceanography (MIO), Aix-Marseille University, 13288, Marseille Cedex 9, France
[ai] Université du Sud Toulon-Var, CNRS-INSU/IRD UM 110, 83957, La Garde Cedex, France
[aj] Dipartimento di Fisica ed Astronomia dell'Università, Viale Andrea Doria 6, 95125 Catania, Italy
[ak] Direction des Sciences de la Matière, Institut de recherche sur les lois fondamentales de l'Univers, Service de Physique des Particules, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France
[al] INFN – Sezione di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy
[am] Dipartimento di Fisica dell'Università, Largo B. Pontecorvo 3, 56127 Pisa, Italy
[an] INFN – Sezione di Napoli, Via Cintia, 80126 Napoli, Italy
[ao] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
[ap] University Mohammed V in Rabat, Faculty of Sciences, 4 av. Ibn Battouta, B.P. 1014, R.P. 10000 Rabat, Morocco
[aq] Dipartimento di Fisica dell'Università Federico II di Napoli, Via Cintia, 80126, Napoli, Italy

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A B S T R A C T

Using data recorded with the ANTARES telescope from 2007 to 2015, a new search for dark matter annihilation in the Milky Way has been performed. Three halo models and five annihilation channels, $\mathrm{WIMP}+\mathrm{WIMP}\to \mathrm{b}\bar{\mathrm{b}}, \mathrm{W}^+\mathrm{W}^-, \tau^+\tau^-, \mu^+\mu^-$ and $\nu\bar{\nu}$, with WIMP masses ranging from 50 $\frac{\mathrm{GeV}}{\mathrm{c}^2}$ to 100 $\frac{\mathrm{TeV}}{\mathrm{c}^2}$, were considered. No excess over the expected background was found, and limits on the thermally averaged annihilation cross-section were set.

1. Introduction

A wide variety of observations supply evidence for the existence of dark matter (DM) [1,2]. Its nature, however, is so-far unknown, and attempts to elucidate it have given rise to a lively and varied research programme in physics. A common hypothesis is to consider dark matter to be made of new, unknown particles. The assumption that these particles are a thermal relic of the Big Bang leads to the conclusion that they are weakly interacting massive particles (WIMPs).

Different approaches are used to search for these particles: production at particle accelerators [3], direct detection of the recoil from collisions with nuclei [4] or indirect detection by means of the secondary particles that they produce when they decay or annihilate [5]. Most of the particles that have been put forward as WIMPs candidates annihilate in pairs and subsequently produce standard model particles, including neutrinos. Neutrino telescopes may play a paramount role in the search for WIMPs via their annihilation products, because of their particularly clean signals and low expected backgrounds.

In this paper the results from the search for dark matter in the Milky Way using data recorded with the ANTARES neutrino telescope from 2007 to 2015, with a total live time of 2102 days are presented. Only neutrinos detected via muons produced inside or around the detector are considered. Here and in the following "neutrino" means $\nu_\mu + \bar{\nu}_\mu$, unless stated otherwise.

In Section 2 it is presented how the neutrino flux can be derived from the annihilation of DM particles. The detector and the reconstruction method are described in Section 3, while the new analysis methodology is explained in Section 4. The results are presented in Section 5.

Compared to work previously published [6], a considerably increased data sample is used and a maximum likelihood method or "unbinned method" is applied. In addition, more recent parameters for the DM halo in the Milky Way are used.

2. Dark matter phenomenology

In this type of indirect search two important ingredients have to be considered: the amount and spatial distribution of dark matter in the source under consideration, and the energy spectra of the standard model particles produced by WIMP annihilation. These two features are to a large extent independent of each other. They are relevant for modelling the expected signal and enter into the analysis at different stages.

The signal spectra used for the analysis presented here were calculated using the code described in [7]. Spectra were obtained for five annihilation channels and 17 WIMP masses between 50 $\frac{\mathrm{GeV}}{\mathrm{c}^2}$ and 100 $\frac{\mathrm{TeV}}{\mathrm{c}^2}$. These spectra take into account the effect of neutrino oscillations. In the following, the results for each annihilation channel are given assuming a 100% branching ratio. The five annihilation channels are:

$$\mathrm{WIMP}+\mathrm{WIMP}\to \mathrm{b}\bar{\mathrm{b}}, \mathrm{W}^+\mathrm{W}^-, \tau^+\tau^-, \mu^+\mu^-, \nu_\mu\bar{\nu}_\mu. \quad (1)$$

Of these channels, the $b\bar{b}$-channel produces the softest neutrino spectra, whilst the $\nu_\mu\bar{\nu}_\mu$-channel produces the hardest spectra. Although the $\nu_\mu\bar{\nu}_\mu$-channel is suppressed in many models, such as those with the WIMP being the lightest neutralino of supersym-

* Corresponding author.
E-mail address: ctoennis@ific.uv.es (C. Tönnis).

Table 1
Table of dark matter halo parameters for the Milky Way as taken from [10] and [11]. ρ_{local} is the local density and r_s is the scaling radius.

Parameter	NFW	Burkert	McMillan
r_s [kpc]	$16.1^{+17.0}_{-7.8}$	$9.26^{+5.6}_{-4.2}$	17.6 ± 7.5
ρ_{local} [GeV/cm^3]	$0.471^{+0.048}_{-0.061}$	$0.487^{+0.075}_{-0.088}$	0.390 ± 0.034

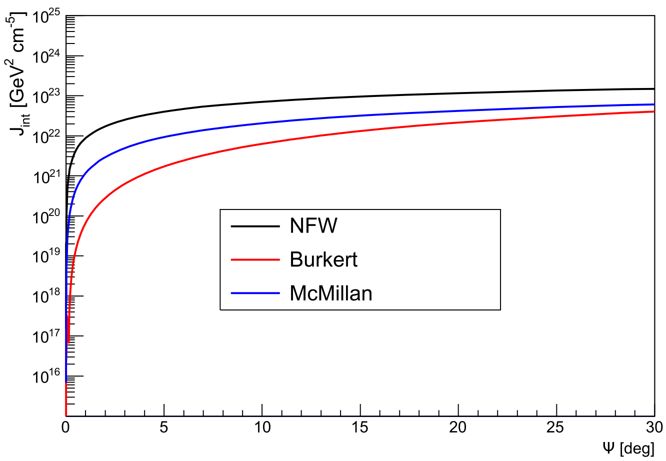


Fig. 1. The integrated J-Factor, J_{int}, for a cone-shaped region $\Delta\Omega$ centred on the Galactic Centre with an opening angle Ψ. For the halo models the parameters from Table 1 are used. The calculations are done using the code CLUMPY [13].

metric models, it is included in this study in order to be as model independent as possible.

The second ingredient, i.e. the amount and distribution of dark matter in the source, is described by the so-called J-Factor. The J-Factor, $J(\psi)$, is the integral of the dark matter density squared, ρ^2_{DM}, over a line of sight at an angular separation ψ from the centre of the source. The relative signal strength at an angular separation ψ to the source is described by the expression $J(\psi)d\Omega(\psi)$. The J-Factor can be integrated over an observation window $\Delta\Omega$:

$$\mathrm{J_{int}}(\Delta\Omega) = \int\limits_{\Delta\Omega} \int \rho^2_{\mathrm{DM}} \cdot \mathrm{dl} \cdot \mathrm{d}\Omega. \tag{2}$$

$\mathrm{J_{int}}$ relates the thermally averaged annihilation cross-section $\langle \sigma \mathrm{v} \rangle$ to the neutrino flux $\Phi_{\nu_\mu+\bar{\nu}_\mu}$ via the following equation:

$$\frac{\mathrm{d}\Phi_{\nu_\mu+\bar{\nu}_\mu}}{\mathrm{dE}_{\nu_\mu+\bar{\nu_\mu}}} = \frac{\langle \sigma \mathrm{v} \rangle}{8\pi \mathrm{M}^2_{\mathrm{WIMP}}} \cdot \frac{\mathrm{dN}_{\nu_\mu+\bar{\nu}_\mu}}{\mathrm{dE}_{\nu_\mu+\bar{\nu}_\mu}} \cdot \mathrm{J_{int}}(\Delta\Omega), \tag{3}$$

where $\mathrm{N}_{\nu_\mu+\bar{\nu}_\mu}$ is the average number of neutrinos in the energy bin $\mathrm{dE}_{\nu_\mu+\bar{\nu}_\mu}$ per WIMP annihilation, v is the WIMP velocity and $\mathrm{M_{WIMP}}$ is the WIMP mass.

The shape of the J-Factor crucially depends on the halo model. In this analysis three models are used: the NFW [8], the Burkert [9] model and the "McMillan" [10] profile. The parameters for these models are taken from [11] and [10] and are shown in Table 1. The McMillan profile is a variant of the Zhao profile [12], which treats one of the shape parameters, γ, as a free parameter and therefore is also referred to as the "γ free" model. The optimum value of γ for this model is 0.79 ± 0.32. The uncertainties on the halo profile parameters are not used in this analysis. In Fig. 1 the integrated J-Factors for the three models are shown. The NFW profile gives a larger total amount of dark matter that is also more concentrated in the core of the source than for the Burkert profile. This is due to the fact that the NFW profile is a so-called cuspy profile and diverges at the centre of the source, in contrast to the cored Burkert profile.

3. Simulation and reconstruction

The

the background events, respectively, as a function of the relevant event variables. The likelihood is then maximised by varying n_s. The statistical significance of the value obtained is extracted from the distribution of maximum likelihoods produced by generating pseudo-experiments, i.e. samples of events with known amounts of background and signal. The likelihood function used has the form

$$\mathcal{L}(n_s) = e^{-(n_s+N_{bg})} \prod_{i=1}^{N_{tot}} \left(n_s S(\psi_i, N_{hit,i}, \beta_i) + N_{bg} B(\psi_i, N_{hit,i}, \beta_i) \right), \quad (4)$$

where N_{bg} is the expected number of background events, which is set equal to N_{tot}, the total number of reconstructed events. n_s is the variable that changes during the maximisation process. The two functions S and B depend on: ψ_i, the angular distance of the i-th event to the centre of the Milky WayE

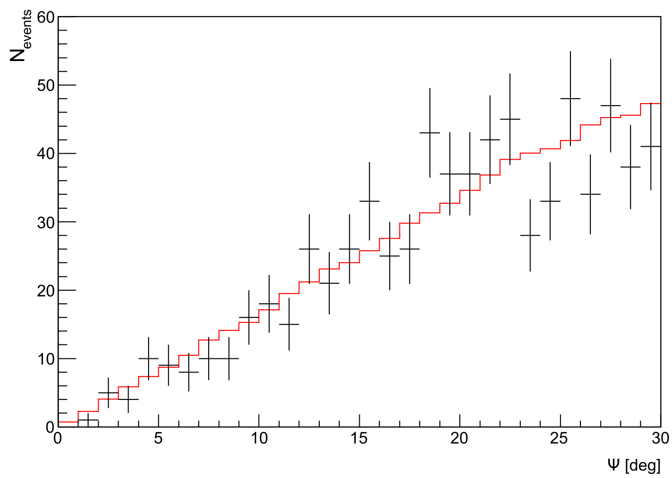


Fig. 2. The number of events as a function of the distance to the Galactic Centre (crosses) in comparison to the background estimate (red line) for the ΛFit reconstruction. For this plot a quality cut of $\Lambda > -5.2$ is used. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

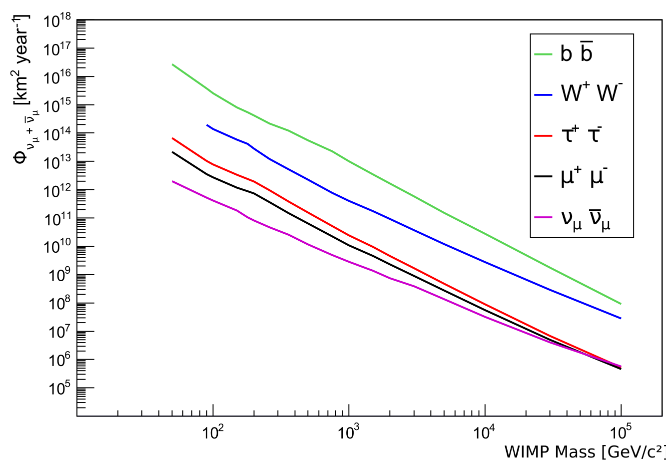
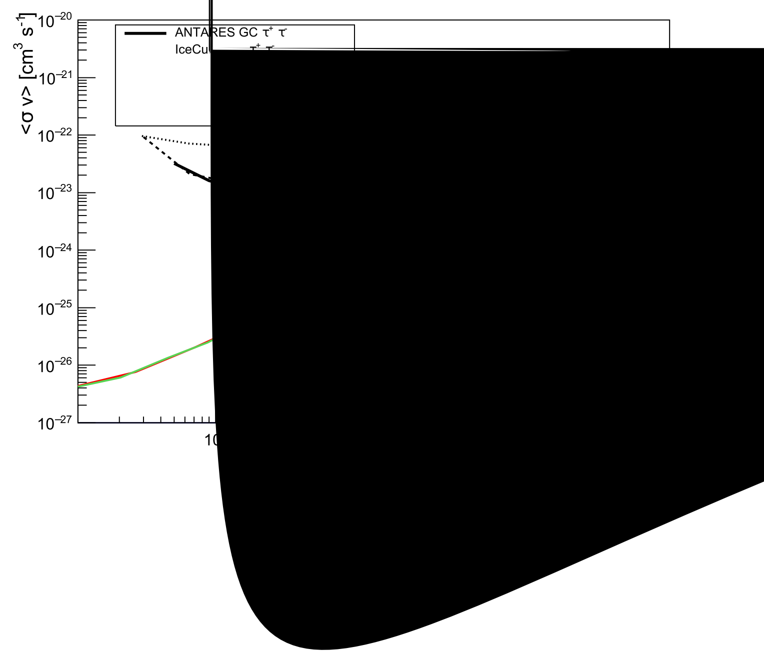


Fig. 3. 90% C.L. upper limits on the neutrino flux from WIMP annihilations in the Milky Way as a function of the WIMP masses for the different channels considered. For this plot the NFW profile was used.



background can be seen, which is consistent with the fact that all the TS_{obs} values obtained are smaller than the medians of the corresponding background TS distributions. Since all background-like results should equally reject the considered dark matter model, upper limits have been set to the sensitivities calculated from the pseudo-experiments.

The resulting upper limits in terms of neutrino flux are shown in Fig. 3. For each annihilation channel and WIMP mass range, the reconstruction strategy, QFit or ΛFit, which gives the best sensitivity is used in the final result. ΛFit is used for $M_{WIMP} \geq 260\ \frac{GeV}{c^2}$ for the $\tau^+\tau^-$ and $\mu^+\mu^-$ channels; for $M_{WIMP} \geq 750\ \frac{GeV}{c^2}$ for the $b\bar{b}$ channel; for $M_{WIMP} \geq 150\ \frac{GeV}{c^2}$ for W^+W^- and for $M_{WIMP} \geq 100\ \frac{GeV}{c^2}$ for the $\nu_\mu\bar{\nu}_\mu$ channel. For the remaining values, i.e. at low WIMP masses, the QFit results are used.

From the limits on the neutrino flux, limits on $\langle\sigma v\rangle$ can be derived. The 90% C.L. upper limit on $\langle\sigma v\rangle$ for the $\tau^+\tau^-$ channel as a function of the WIMP mass is shown in Fig. 4, compared with limits obtained by other indirect searches. Most of the direct search experiments are not directly sensitive to $\langle\sigma v\rangle$. The limits for all annihilation channels for the NFW halo profile are shown in Fig. 5.

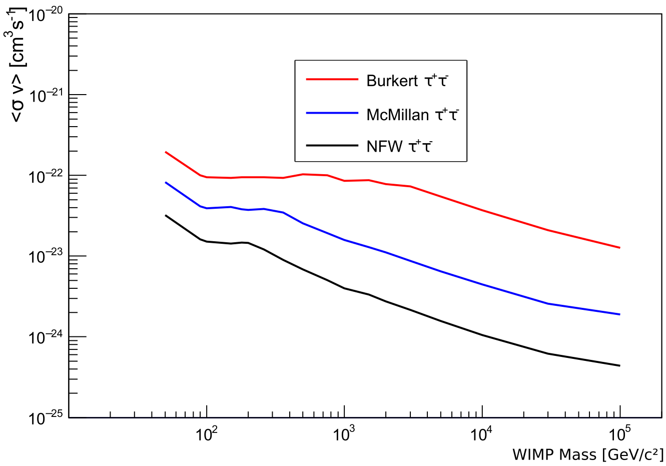


Fig. 6. 90% C.L. limits on the thermally averaged annihilation cross-section, $\langle\sigma v\rangle$, as a function of the WIMP mass for the three considered halo models for the $\tau^+\tau^-$ channel.

ity [38] will become relevant, although there is an approach to overcome these limitations [39].

In order to illustrate the large effect of the choice of the halo model and the profile parameters, a comparison between upper limits derived using the NFW, the Burkert and the McMillan results is shown in Fig. 6 for the $\tau^+\tau^-$ channel. As can be seen, depending on the WIMP mass, differences of more than one order of magnitude are observed between the different halo models.

6. Conclusions

The results from a new search for dark matter annihilation in the Milky Way using data from the ANTARES neutrino telescope from 2007 to 2015 show no excess above the expected background. Limits at 90% C.L. have been set for the NFW, the McMillan and the Burkert profile, five annihilation channels and WIMP masses ranging from 50 $\frac{\text{GeV}}{c^2}$ to 100 $\frac{\text{TeV}}{c^2}$. These limits are the most stringent for a certain region of the parameter space.

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