PROCEEDINGS OF SCIENCE

Indirect dark matter searches towards the Sun using the full ANTARES data set

Chiara Poirè[a,*] and Juan García Mendéz[b] on behalf of the ANTARES Collaboration

[a] *Università di Salerno e INFN Gruppo Collegato di Salerno, Dipartimento di Fisica, Via Giovanni Paolo II 132, Fisciano, 84084, Italy*

[b] *Institut d'Investigació per a la Gestió Integrada de les Zones Costaneres(IGIC)-Universitat Politècnica de València, C/Paranimf 1, 46730 Gandia, Spain*

E-mail: cpoire@unisa.it, jgarmen@upvnet.upv.es

Weakly Interacting Massive Particles (WIMPs) are among the most compelling candidates for particle dark matter. These particles can be gravitationally captured by massive celestial bodies, such as the Sun, where they accumulate and, according to theoretical models, eventually self-annihilate into Standard Model particles, including neutrinos. Neutrino telescopes - large arrays of photo-sensors in a transparent medium - can search for this indirect signature of dark matter by detecting neutrinos originating from the Sun's core. In this study, data collected from 2007 to 2022 by ANTARES, a neutrino telescope in the Mediterranean Sea, are analyzed to perform an indirect search for dark matter from the direction of the Sun. Neutrino event properties are reconstructed using standard algorithms developed within the Collaboration, alongside a novel Machine Learning tool designed to enhance reconstruction accuracy for neutrino energies below 200 GeV, applied for the first time in this type of analysis. Additionally, all-flavor neutrino interactions are considered. A likelihood-based unbinned analysis is conducted to determine the upper limits to the spin-dependent and spin-independent WIMP- nucleon scattering cross-sections for WIMP masses ranging from 35 GeV/c^2 to 10 TeV/c^2 and for three different annihilation channels.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

*Speaker

PoS(ICRC2025)515

1. Introduction

The existence of dark matter was first inferred by Zwicky in 1933 [1], through the analysis of the velocity dispersion of galaxies within the Coma cluster. Since then, a multitude of theoretical models have been developed to describe its nature, and various experimental approaches have been pursued to test these hypotheses.
Among the most extensively investigated dark matter candidates are Weakly Interacting Massive Particles (WIMPs) [6, 7]. These hypothetical particles are expected to interact with ordinary matter via weak nuclear interactions and gravity. WIMPs can undergo self-annihilation, producing Standard Model particles, which may subsequently yield neutrinos[7]. Due to these properties, WIMPs can accumulate in massive astrophysical bodies, such as the Sun, one of the most favorable nearby targets for indirect dark matter detection. Assuming a known local dark matter density, WIMPs may scatter off solar nucleons, lose energy through these interactions, and become gravitationally captured in the Sun's core, where they may accumulate over time. Their subsequent annihilation could produce a flux of neutrinos that can escape the Sun and be detected at Earth.
The analysis presented in this document describes the upper limits, considering the Sun as a neutrino source from WIMP annihilation. Three WIMP annihilation channels ($b\bar{b}$, $\tau^+\tau^-$, W^+W^-) are considered, as well as WIMP masses ranging from 35 GeV/c^2 to 10 TeV/c^2 to compute the expected signal neutrino flux, using data collected by the ANTARES neutrino telescope from 2007 to 2022.

2. The ANTARES neutrino telescope

The ANTARES detector [2] was the first neutrino telescope to be deployed in deep sea water, located in the Mediterranean Sea. Data-taking began in 2007, with the full detector completed in 2008. ANTARES operated continuously until February 2022 and was dismantled during the summer of the same year.
The detector was anchored to the seabed at a depth of approximately 2500 meters, about 40 km offshore from the French town of Toulon. It comprised a three-dimensional array of 885 optical modules (OMs), each oriented 45° downward and distributed along 12 vertical detection lines. Each OM contained a 10-inch photomultiplier tube (PMT) enclosed within a pressure-resistant glass sphere, together with its electronic base, an optical coupling gel, and a μ-metal cage for magnetic shielding. The OMs were arranged in triplets (referred to as storeys), with 25 storeys per line and a vertical spacing of 14.5 meters between them. Each line was 450 meters long and was kept taut by a buoy at its top. The horizontal spacing between lines were ranging from 60 to 75 meters. Each line was deployed from a ship and connected to a central junction box on the seabed by a remotely operated submarine vehicle. The junction box was connected to the onshore control station via an electro-optical cable.
The detector was equipped with several calibration systems [9]. Due to sea currents (up to 20 cm/s), the lines were able to sway laterally, with displacements of up to approximately 15 meters at the top. To accurately monitor the geometry and positioning of the detector, a system of acoustic transceivers, tiltmeters, and compasses was distributed along the lines. The shape of each line and the orientation of its storeys were reconstructed every two minutes. The acoustic positioning system provided the location of each OM with a precision better than 15 cm.

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3. The Sun as a source of neutrinos from dark matter annihilation

In the framework of indirect dark matter searches, the Sun represents a particularly promising target due to its proximity and its capability to gravitationally capture Weakly Interacting Massive Particles (WIMPs). As the Sun moves through the Galactic halo, WIMPs may scatter off solar nuclei and lose enough kinetic energy to become gravitationally bound [11]. Over time, these particles accumulate in the solar core, where their number density can increase significantly. If WIMPs are Majorana particles, they can self-annihilate, producing Standard Model particles such as quarks, gauge bosons, or leptons. These annihilation products rapidly decay or hadronize, that can yeald into neutrinos [8, 12]. Unlike other annihilation products, neutrinos can escape the dense solar medium and propagate to Earth, where they can be detected by neutrino telescopes [10]. The energy spectrum and flux of the resulting neutrinos depend on the annihilation channel and the WIMP mass. Hard channels, such as W^+W^- or $\tau^+\tau^-$, typically produce more energetic neutrinos compared to softer channels like $b\bar{b}$. Additionally, the capture-annihilation equilibrium condition in the Sun can be assumed for most WIMP models, which allows the neutrino flux to be directly related to the WIMP-nucleon scattering cross-section. Detecting an excess of neutrinos from the direction of the Sun, above the expected atmospheric neutrino background, would provide strong evidence for WIMP dark matter and offer insights into its particle nature and interaction strength [10].

The WimpSim software [4] has been used to simulate the self-annihilation of dark matter particles in the Sun, and to obtain the corresponding SM energy spectrum at Earth; this also accounts for the effects of neutrino oscillation along the neutrino path from the Sun to the Earth.

4. Search method

Three different reconstruction strategies have been used to determine the direction of the incoming neutrinos. *Method 1* is a machine learning algorithm which reconstructs events detected only in one line in particular for low neutrino energies, boosting the sensitivity to low dark matter masses [16]. *Method 2* is a χ^2-like fit and it is most effective for low/intermediate dark matter masses [15]. *Method 3* is a maximum likelihood method, which is optimal for the search of high dark matter masses [14].

In the ANTARES Collaboration, a *run-by-run* [17] simulation approach is used, allowing to reproduce the time-dependent evolution of the detector. Different selection cuts are tested using Monte Carlo data-sets [17] which simulate the expected signal. The background is estimated by scrambling the time information of the events in the real data.

The analysis is based on an unbinned likelihood:

$$\ln \mathcal{L}(n_s) = \sum_{i=1}^{N} \ln[n_s S(\Psi_{\odot,i}, \beta_i, N_{hits,i}) + n_b B(\Psi_{\odot,i}, \beta_i, N_{hits,i})] - (n_s + n_b) \quad (1)$$

where $S(\Psi_{\odot,i}, \beta_i, N_{hits,i})$ and $B(\Psi_{\odot,i}, \beta_i, N_{hits,i})$ represent the signal and the background Probability Density Functions (PDFs) for the observation of an event at an angular distance $\Psi_{\odot,i}$ from the Sun. n_s and n_b are the number of events from signal and from background respectevely.

This analysis consider track-like events from all the neutrino flavors.

The upper limit on the number of events from DM annihilation can be translated into an estimation of the neutrino flux, which can be written as:

$$\hat{\Phi}^{90\%}_{\nu_\mu+\bar{\nu}_\mu} = \frac{\hat{\mu}_{90\%}}{\bar{A}_{\rm eff}(M_{\rm WIMP}) \cdot T_{\rm eff}}, \quad (2)$$

where $\hat{\mu}_{90\%}$ is the computed upper limit on the number of signal events at 90% confidence level. $T_{\rm eff}$ is the effective livetime of ANTARES between 2007 and 2022, and it corresponds to 12.47 years. In Figure 1 the upper limits for the flux of the three channels considered are shown.
The detector acceptance for the interactions of neutrinos originated from DM annihilation in the Sun can be expressed as

$$\bar{A}_{\rm eff}(M_{\rm WIMP}) = \frac{\sum_{j=\nu,\bar{\nu}} \left(\int_0^{M_{\rm WIMP}} A^j_{\rm eff}(E_j) \frac{dN_j}{dE_j} dE_j \right)}{\int_{5\,GeV}^{M_{\rm WIMP}} \frac{dN_\nu}{dE_\nu} dE_\nu + \frac{dN_{\bar{\nu}}}{dE_{\bar{\nu}}} dE_{\bar{\nu}}}, \quad (3)$$

where $\mathrm{d}N_{\nu(\bar{\nu})}/\mathrm{d}E_{\nu(\bar{\nu})}$ is the energy spectrum of the (anti-)neutrinos at the surface of the Earth, simulated using WimpSim [4] for each of the considered channels, $b\bar{b}$, $\tau^+\tau^-$ and W^+W^-. The integral at denominator starts from 5 GeV, which coresponds to the energy treshold of the detector. $A^{\nu,\bar{\nu}}_{\rm eff}(E_{\nu,\bar{\nu}})$ is the effective area of the ANTARES detector as a function of the (anti-)neutrino energy, depending on the selection cuts. Since all neutrino flavors have been considered, the final acceptance is the sum of the single acceptance of each flavor. The acceptance obtained using *Method 3* is presented in Figure 2, for all the channels considered.

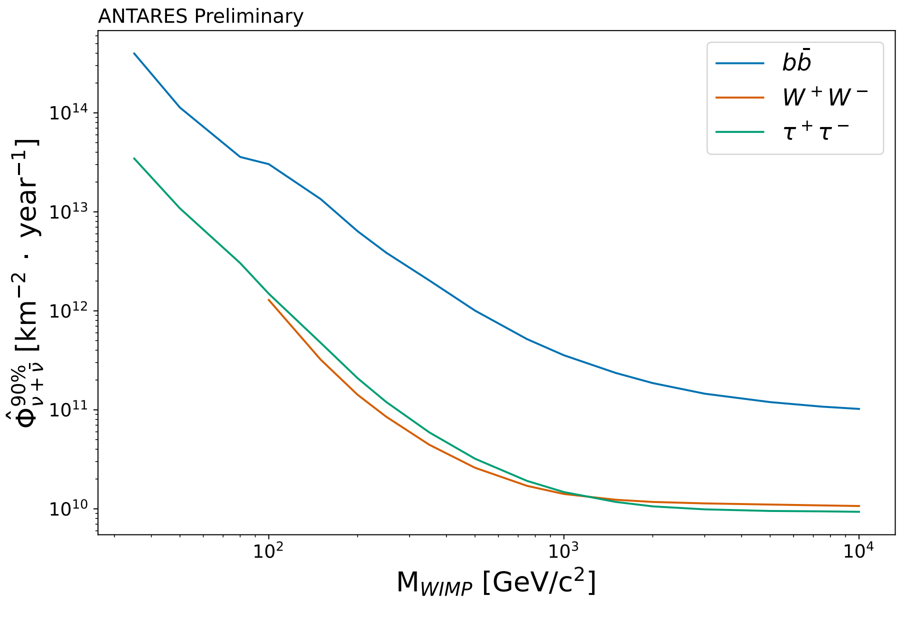

Figure 1: Upper limits on the flux for the indirect search of dark matter towards the Sun, using 4551 livetime days of ANTARES data (2007-2022).

No significant excess of events has been measured and upper limits on neutrino flux have been set (Figure 1). The neutrino flux upper limit can be converted into cross section upper limit [12].

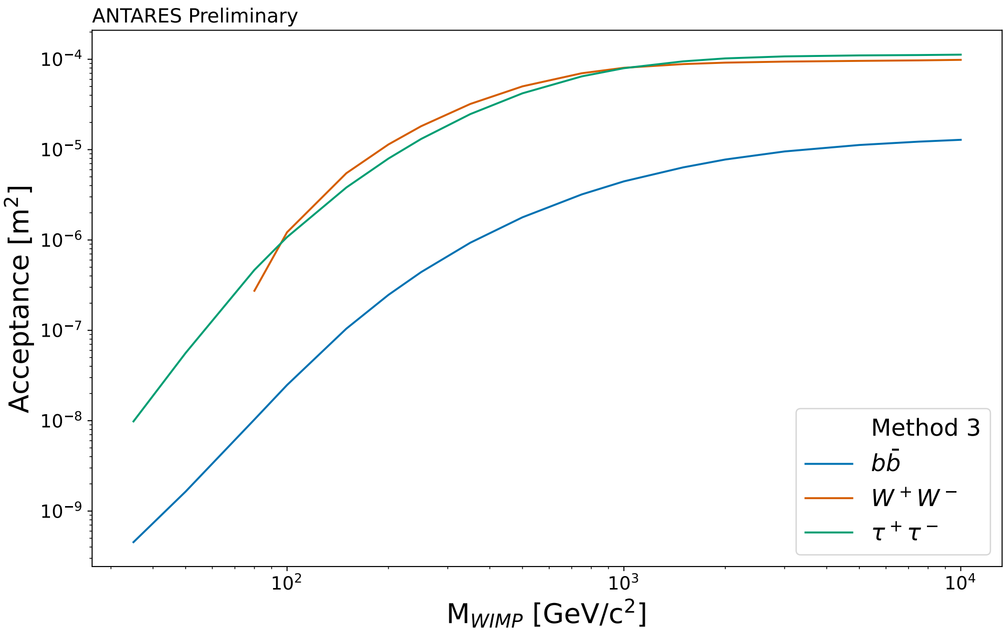

Figure 2: Acceptance of the detector for the three channels using the *Method 3*.

The indirect search for dark matter towards the Sun allows to distinguish between two cases: spin dependent and spin independent cross sections. The results of this analysis have been compared with the upper limits of other experiments, both direct and indirect dark matter searches. The preliminary results are shown in Figure 3 for the spin-dependent case and in Figure 4 for the spin-independent.

5. Conclusions

The analysis presented here uses 15 years (2007-2022) of data collected by the ANTARES neutrino telescope to constrain the DM-nucleon scattering cross section in the Sun. The search for neutrinos produced from the annihilation of DM particles in the Sun allows to constrain both the spin-dependent and the spin-independent WIMP-nucleon cross section. The results obtained in this work improve upon those previously published by ANTARES, which used a dataset from 2007 to 2012 [18]. These upper limits are competitive with those obtained in both direct and indirect searches above DM mass of 100 GeV/c^2. In the case of spin-dependent WIMP-nucleon scattering, the limits obtained in the above-mentioned DM mass range are more stringent than those from direct detection experiments, similarly to what is obtained in other indirect searches. The next generation neutrino observatory in the Mediterranean Sea, KM3NeT [24], currently under construction and already taking data, is also performing these searches [25].

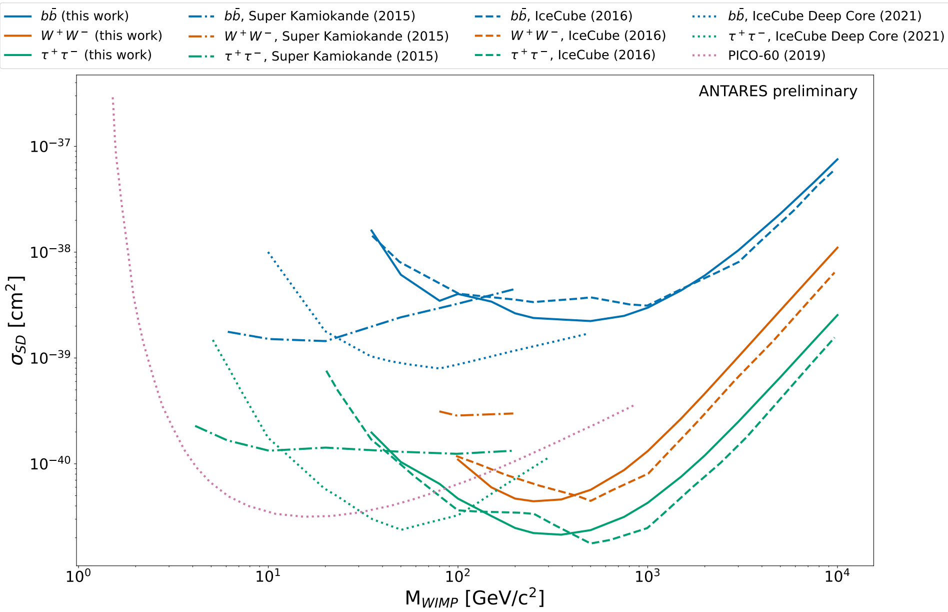

Figure 3: Limits on the spin–dependent WIMP–nucleon scattering cross section as a function of WIMP mass for the $b\bar{b}$ (blue), $\tau^+\tau^-$ (green) and W^+W^- (orange) channels. Limits given by other experiments are also shown: IceCube [19, 20], PICO-60 [22], SuperKamiokande [21].

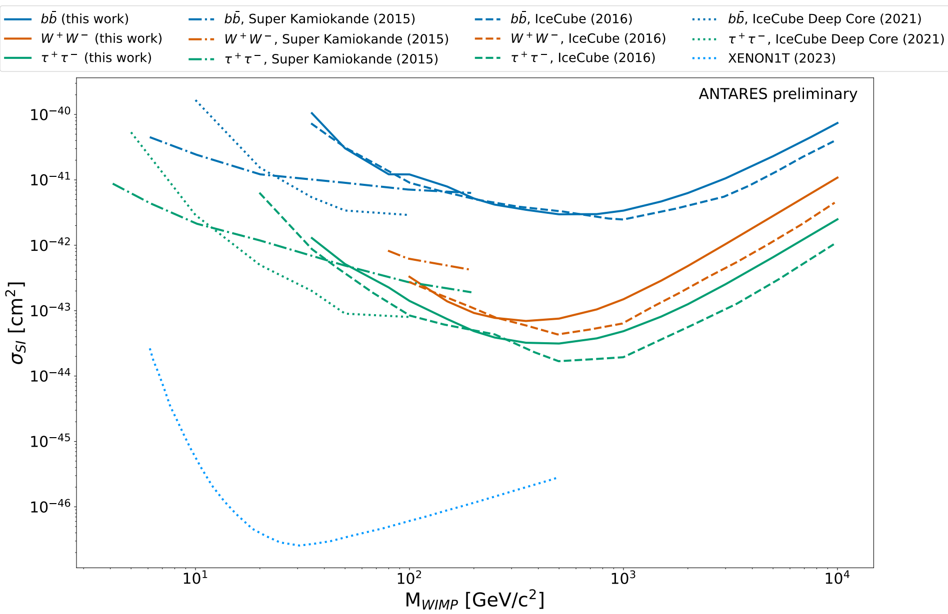

Figure 4: Limits on the spin–independent WIMP–nucleon scattering cross section as a function of WIMP mass for the $b\bar{b}$ (blue), $\tau^+\tau^-$ (green) and W^+W^- (orange) channels. Limits given by other experiments are also shown: IceCube [19, 20], XENONnT [23], SuperKamiokande [21].

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Full Authors List: The ANTARES Collaboration

A. Albert[a,b], S. Alves[c], M. André[d], M. Ardid[e], S. Ardid[e], J.-J. Aubert[f], J. Aublin[g], B. Baret[g], S. Basa[h], Y. Becherini[g], B. Belhorma[i], F. Benfenati[j,k], V. Bertin[f], S. Biagi[l], J. Boumaaza[m], M. Bouta[n], M.C. Bouwhuis[o], H. Brânzaş[p], R. Bruijn[o,q], J. Brunner[f], J. Busto[f], B. Caiffi[r], D. Calvo[c], S. Campion[s,t], A. Capone[s,t], F. Carenini[j,k], J. Carr[f], V. Carretero[c], T. Cartraud[g], S. Celli[s,t], L. Cerisy[f], M. Chabab[u], R. Cherkaoui El Moursli[m], T. Chiarusi[j], M. Circella[v], J.A.B. Coelho[g], A. Coleiro[g], R. Coniglione[l], P. Coyle[f], A. Creusot[g], A. F. Díaz[w], B. De Martino[f], C. Distefano[l], I. Di Palma[s,t], C. Donzaud[g,x], D. Dornic[f], D. Drouhin[a,b], T. Eberl[y], A. Eddymaoui[m], T. van Eeden[o], D. van Eijk[o], S. El Hedri[g], N. El Khayati[m], A. Enzenhöfer[f], P. Fermani[s,t], G. Ferrara[l], F. Filippini[j,k], L. Fusco[z], S. Gagliardini[s,t], J. García-Méndez[e], C. Gatius Oliver[o], P. Gay[aa,g], N. Geißelbrecht[y], H. Glotin[ab], R. Gozzini[c], R. Gracia Ruiz[y], K. Graf[y], C. Guidi[r,ac], L. Haegel[g], H. van Haren[ad], A.J. Heijboer[o], Y. Hello[ae], L. Hennig[y], J.J. Hernández-Rey[c], J. Hößl[y], F. Huang[f], G. Illuminati[j,k], B. Jisse-Jung[o], M. de Jong[o,af], P. de Jong[o,q], M. Kadler[ag], O. Kalekin[y], U. Katz[y], A. Kouchner[g], I. Kreykenbohm[ah], V. Kulikovskiy[r], R. Lahmann[y], M. Lamoureux[g], A. Lazo[c], D. Lefèvre[ai], E. Leonora[aj], G. Levi[j,k], S. Le Stum[f], S. Loucatos[ak,g], J. Manczak[c], M. Marcelin[h], M. Marconi[r,ac], A. Margiotta[j,k], A. Marinelli[al,am], J.A. Martínez-Mora[e], P. Migliozzi[al], A. Moussa[n], R. Muller[o], S. Navas[an], E. Nezri[h], B. Ó Fearraigh[o], E. Oukacha[g], A.M. Păun[p], G.E. Păvălaş[p], S. Peña-Martínez[g], M. Perrin-Terrin[f], P. Piattelli[l], C. Poirè[z], V. Popa[p], T. Pradier[a], N. Randazzo[aj], D. Real[c], G. Riccobene[l], A. Romanov[r,ac], A. Sánchez Losa[c], A. Saina[c], F. Salesa Greus[c], D. F. E. Samtleben[o,af], M. Sanguineti[r,ac], P. Sapienza[l], F. Schüssler[ak], J. Seneca[o], M. Spurio[j,k], Th. Stolarczyk[ak], M. Taiuti[r,ac], Y. Tayalati[m], B. Vallage[ak,g], G. Vannoye[f], V. Van Elewyck[g,ao], S. Viola[l], D. Vivolo[ap,al], J. Wilms[ah], S. Zavatarelli[r], A. Zegarelli[s,t], J.D. Zornoza[c], J. Zúñiga[c].

[a] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
[b] Université de Haute Alsace, F-68100 Mulhouse, France
[c] IFIC - Instituto de Física Corpuscular (CSIC - Universitat de València) c/ Catedrático José Beltrán, 2 E-46980 Paterna, Valencia, Spain
[d] Technical University of Catalonia, Laboratory of Applied Bioacoustics, Rambla Exposició, 08800 Vilanova i la Geltrú, Barcelona, Spain
[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 Univ, CNRS/IN2P3, CPPM, Marseille, France
[g] Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
[h] Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France
[i] National Center for Energy Sciences and Nuclear Techniques, B.P.1382, R. P.10001 Rabat, Morocco
[j] INFN - Sezione di Bologna, Viale Berti-Pichat 6/2, 40127 Bologna, Italy
[k] Dipartimento di Fisica e Astronomia dell'Università di Bologna, Viale Berti-Pichat 6/2, 40127, Bologna, Italy
[l] INFN - Laboratori Nazionali del Sud (LNS), Via S. Sofia 62, 95123 Catania, Italy
[m] University Mohammed V in Rabat, Faculty of Sciences, 4 av. Ibn Battouta, B.P. 1014, R.P. 10000 Rabat, Morocco
[n] University Mohammed I, Laboratory of Physics of Matter and Radiations, B.P.717, Oujda 6000, Morocco
[o] Nikhef, Science Park, Amsterdam, The Netherlands
[p] Institute of Space Science - INFLPR subsidiary, 409 Atomistilor Street, Măgurele, Ilfov, 077125 Romania
[q] Universiteit van Amsterdam, Instituut voor Hoge-Energie Fysica, Science Park 105, 1098 XG Amsterdam, The Netherlands
[r] INFN - Sezione di Genova, Via Dodecaneso 33, 16146 Genova, Italy
[s] INFN - Sezione di Roma, P.le Aldo Moro 2, 00185 Roma, Italy
[t] Dipartimento di Fisica dell'Università La Sapienza, P.le Aldo Moro 2, 00185 Roma, Italy
[u] LPHEA, Faculty of Science - Semlali, Cadi Ayyad University, P.O.B. 2390, Marrakech, Morocco.
[v] INFN - Sezione di Bari, Via E. Orabona 4, 70126 Bari, Italy
[w] Department of Computer Architecture and Technology/CITIC, University of Granada, 18071 Granada, Spain
[x] Université Paris-Sud, 91405 Orsay Cedex, France
[y] Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics, Erwin-Rommel-Str. 1, 91058 Erlangen, Germany
[z] Università di Salerno e INFN Gruppo Collegato di Salerno, Dipartimento di Fisica, Via Giovanni Paolo II 132, Fisciano, 84084 Italy
[aa] Laboratoire de Physique Corpusculaire, Clermont Université, Université Blaise Pascal, CNRS/IN2P3, BP 10448, F-63000 Clermont-Ferrand, France
[ab] LIS, UMR Université de Toulon, Aix Marseille Université, CNRS, 83041 Toulon, France
[ac] Dipartimento di Fisica dell'Università, Via Dodecaneso 33, 16146 Genova, Italy
[ad] Royal Netherlands Institute for Sea Research (NIOZ), Landsdiep 4, 1797 SZ 't Horntje (Texel), the Netherlands
[ae] Géoazur, UCA, CNRS, IRD, Observatoire de la Côte d'Azur, Sophia Antipolis, France
[af] Huygens-Kamerlingh Onnes Laboratorium, Universiteit Leiden, The Netherlands
[ag] Institut für Theoretische Physik und Astrophysik, Universität Würzburg, Emil-Fischer Str. 31, 97074 Würzburg, Germany
[ah] Dr. Remeis-Sternwarte and ECAP, Friedrich-Alexander-Universität Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany
[ai] Mediterranean Institute of Oceanography (MIO), Aix-Marseille University, 13288, Marseille, Cedex 9, France; Université du Sud Toulon-Var, CNRS-INSU/IRD UM 110, 83957, La Garde Cedex, France
[aj] INFN - Sezione di Catania, Via S. Sofia 64, 95123 Catania, Italy
[ak] IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
[al] INFN - Sezione di Napoli, Via Cintia 80126 Napoli, Italy

[am]Dipartimento di Fisica dell'Università Federico II di Napoli, Via Cintia 80126, Napoli, Italy
[an]Dpto. de Física Teórica y del Cosmos & C.A.F.P.E., University of Granada, 18071 Granada, Spain
[ao]Institut Universitaire de France, 75005 Paris, France
[ap]Dipartimento di Matematica e Fisica dell'Università della Campania L. Vanvitelli, Via A. Lincoln, 81100, Caserta, Italy

Acknowledgement

The authors acknowledge the financial support of the funding agencies: Centre National de la Recherche Scientifique (CNRS), Commissariat à l'énergie atomique et aux énergies alternatives (CEA), Commission Européenne (FEDER fund and Marie Curie Program), LabEx UnivEarthS (ANR-10-LABX-0023 and ANR-18-IDEX-0001), Région Alsace (contrat CPER), Région Provence-Alpes-Côte d'Azur, Département du Var and Ville de La Seyne-sur-Mer, France; Bundesministerium für Bildung und Forschung (BMBF), Germany; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Nederlandse organisatie voor Wetenschappelijk Onderzoek (NWO), the Netherlands; Ministry of Education and Scientific Research, Romania; MCIN for PID2021-124591NB-C41, -C42, -C43 and PDC2023-145913-I00 funded by MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe", for ASFAE/2022/014 and ASFAE/2022 /023 with funding from the EU NextGenerationEU (PRTR-C17.I01) and Generalitat Valenciana, for Grant AST22_6.2 with funding from Consejería de Universidad, Investigación e Innovación and Gobierno de España and European Union - NextGenerationEU, for CSIC-INFRA23013 and for CNS2023-144099, Generalitat Valenciana for CIDEGENT/2020/049, CIDEGENT/2021/23, CIDEIG/2023/20, ESGENT2024/24, CIPROM/2023/51, GRISOLIAP/2021/192 and INNVA1/2024/110 (IVACE+i), Spain; Ministry of Higher Education, Scientific Research and Innovation, Morocco, and the Arab Fund for Economic and Social Development, Kuwait. We also acknowledge the technical support of Ifremer, AIM and Foselev Marine for the sea operation and the CC-IN2P3 for the computing facilities.