EPJ Web of Conferences **319**, 03003 (2025) https://doi.org/10.1051/epjconf/202531903003
RICAP-24

Indirect Searches for Dark Matter with Neutrino Telescopes

Sara Rebecca Gozzini[1,*]

[1]Instituto de Física Corpuscular, Parque Científico, Catedrático José Beltrán 2, 46980 Paterna, Spain

Abstract.
Extraterrestrial messengers can probe the presence of dark matter in the Milky Way and beyond. Among others, sizable anomalous fluxes of high-energy neutrinos expected from pair annihilation and decay of dark matter particles, giving neutrino telescopes a role in *indirect searches*. The energy features and space distribution of dark matter overdensity regions are used to characterise a signal to be discriminated from an atmospheric neutrino background. Other than in the main gravitational reservoir at the Galactic Centre, dark matter can be trapped in the Sun by losing energy in interaction with baryons. Its annihilation into neutrinos offers a unique opportunity when searching for a signal from the Sun, for which neutrino telescopes have almost no competitors. This lecture gives a review of experimental methods and results on indirect dark matter searches obtained with neutrino telescope data.

1 Introduction

Whilst microscopic physics has advanced in the description of matter in its smallest constituents, most of the mass in the Universe is dark and its nature remains unexplained. This includes the halo of our own Milky Way, that like other galaxies hosts a concentration of non-luminous matter gravitationally accumulated at its centre, and whose presence is evidenced by macroscopic observations [1–3]. For the purpose of most experimental searches, this unknown substance is described as a new elementary particle, with a rather loose composite sketch over a large parameter space, and numerous, continuously updated efforts to determine what this *dark matter* should *not* be. Exactly because properties relevant for detection (mass, interaction strength with ordinary baryonic matter) are unconstrained over a huge range of values, triangulation is crucial between complementary search approaches: production, direct, indirect. A common assumption underlying experimental searches is that dark matter plays a role in the thermal history of the universe. Thermal freeze-out of species in the Early Universe explains their relative abundances as observed nowadays. In the Λ_{CDM} model, hosting dark matter as a thermal relic, WIMPs (weakly interacting massive particles) raise particular attention: their interaction strength is coincidentally of the size of the known electroweak interaction, introducing no new scale in the theory, and matching at the same time the observed dark matter abundance [4, 5]. Low interaction rates require large detection volumes, which is for instance the current limiting factor for direct searches in noble gas or scintillators. Indirect searches target dark matter in astrophysical environment, in regions where it accumulates to high densities. At the same time, low interaction rates ensure that some dark matter is still to be found nowadays as a thermal relic.

---

[*] e-mail: srgozzini@km3net.de

2 Dark Matter Messengers: Neutrinos

A handful of cosmic messengers can act as dark matter tracers: photons, neutrinos, electrons, positrons, protons, antiprotons, hydrogen (deuterium, antideuterium) [6]. Like photons, neutrinos participate in proper astronomy, in which they preserve their source information, crossing matter undeflected and unabsorbed[1]. Exactly for these same features, neutrinos are experimentally elusive. They are indirectly detected via an associated lepton. Due to the low interaction rate typical of electroweak processes, neutrinos propagate almost unaffected through the detector too, requiring analyses based on statistics of small signals. This is further challenged by the presence of background from atmospheric leptons not originating from neutrinos: very-large volume neutrino detectors such as KM3NeT [7] and IceCube [8] typically mask out a large amount of this background using the Earth as a filter. Noticeably, the neutrino-nucleon cross section raises with energy [9], compensating the flux of neutrinos from dark matter processes decreasing at higher dark matter masses.

2.1 Flux of Neutrinos from Dark Matter Annihilation

In pair annihilation of dark-matter particles, neutrinos can be produced directly or via an intermediate channel. The final state energy distribution dN_ν^i/dE_ν, corrensponding to channel i, is obtained with a Monte Carlo generator such as HELLWIG or PYTHIA made ready to use through tools such as PPPC4DMID [10] or χaroν [11]. When looking at extended overdensity regions, the dark matter source is described with the J-Factor

$$J_{\text{ANN}} = \int_\Omega d\Omega(\theta, \phi) \int_{l.o.s.} \rho^2\left(s(r, \theta, \phi)\right) ds, \tag{1}$$

with Ω being the solid angle under which the source is observed, s the radial coordinate integrated over the line of sight ($l.o.s.$), and the suffix ANN standing for annihilation. For neutrino telescopes, which have a very broad field of view, values as large as 180° can be considered for the opening angle characterising the solid angle Ω. As an example, the dark matter source at the centre of the Milky Way embeds the entire Earth and beyond. The J-Factor in turn depends on the dark matter density ρ. Simulations of dynamical systems of N particles reproduce accurately the large-scale structures of the current universe (like the distribution of galaxies and galaxy clusters) if assuming the existence of cold dark matter and a expanding universe with a cosmological constant, as predicted in the Λ_{CDM} model. The Navarro-Frenk-White NFW profile [12] is a traditional benchmark motivated by N-Body simulations. In NFW, the dark matter density distribution is characterised by a central cusp, while this is not observed in many galaxies, in particular in those with low masses (dwarf galaxies). Density profiles that are more motivated by the observation of galactic rotation curves are the Isothermal and Burkert profiles [13], characterized by possessing a central core. The shape of the halo profile strongly influences the sensitivity of direct searches in galactic halos, as the more point-like the dark matter source appears, the easier it is to discriminate a flux of neutrinos from an isotropic atmospheric background. Considering the morphology described through the J-Factor and the energy footprint contained in dN_ν^i/dE_ν, the flux of neutrinos from pair annihilation of dark matter is given by

$$\frac{d\Phi_\nu^i}{dE_\nu}(E_\nu) = \frac{1}{4\pi}\,\frac{1}{M_{\text{DM}}^2}\,\frac{\langle\sigma v\rangle}{2}\,\frac{dN_\nu^i}{dE_\nu}(E_\nu)\,J, \tag{2}$$

where M_{DM} is the mass of the dark matter particle, and σ the typical pair-annihilation cross section, thermally averaged over the dark matter velocity distribution as $\langle\sigma v\rangle$.

---

[1] This holds for the direction information. The energy information is generally preserved unless in the case of very dense sources implying internal absorption.

2.2 Flux of Neutrinos from Dark Matter Decay

If considering dark matter decaying into Standard Model particle, the source morphology is described by the J-Factor

$$J_{\mathrm{DEC}} = \int_{d\Omega} \int_{l.o.s.} \rho\,(r(\theta, \phi))\, dr \tag{3}$$

and the flux of outcoming neutrinos through the decay channel i depends on the dark matter lifetime τ_{DM}

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{4\pi} \frac{1}{m_{\mathrm{DM}}} \frac{1}{\tau_{DM}} \frac{dN_\nu^i}{dE_\nu} J_{\mathrm{DEC}}. \tag{4}$$

Additionally, a factor $1/3$ is necessary when considering neutrinos of a given flavour as final states [14]. For dark matter decay, the dependance on the dark matter distribution is weaker than for annihilation, as only one dark matter particle is involved.

3 Uncertainties

The morphology and spectral characterisation of dark matter distributions is affected by uncertainties that propagate on the calculation of neutrino fluxes, inevitably penalizing indirect searches. Also for this motivation a signal from indirect dark matter searches must find confirmation in the direct or production channel.

The largest uncertainties regard the spacial distribution of dark matter halos, which are modeled trying to match the information on dark matter evidence from astrophysics and cosmology. According to the model considered to describe the dark matter halo, upper limits can vary over more than one order of magnitude (see for instance Figure 2 of reference [15]).

Uncertainties also affect the energy distribution of Standard Model particles yield by a dark matter pair-annihilation. Depending on the dark matter mass and annihilation channel considered, uncertainties can amount up to (10% – 30%) mostly reflecting uncertainties on the hadronization model [16].

Other sources of theoretical uncertainties play a role in indirect searches. Classical WIMP annihilation searches generally consider a scenario where each channel independently contributes with a 100% branching ratio. The inclusion of relative branching ratios implies distancing from a model-independent search and including a study of relative amplitudes, which typically evades the reach of these analyses. Finally, a further factor 2 in Equation 2 can be varied according to the choice of Dirac or Majorana dark matter.

4 Characteristic Signatures

4.1 Dark Matter in the Sun

Dark matter particles in the Galactic halo would scatter onto dense celestial bodies such as the Sun loosing a fraction of their energy and eventually falling below the threshold to become gravitationally bound. With the density of those dark matter particles increasing, their probability to pair-annihilate also increments. Under certain age conditions of the accumulator body (conditions that hold for the case of the Sun), an equilibrium is reached between capture and loss through annihilation. In this case the celestial accumulator gives rise to a steady flux of neutrinos from dark matter pair-annihilation that no longer depends on the velocity distribution of dark matter particles in the Galactic halo. A limit on the non-observation of a flux of neutrinos from the Sun with the energy footprint of a dark matter annihilation is therefore translated onto a limit on the dark matter - nucleon scattering cross section. There are two interactions of dark matter with ordinary matter: dependent on spin of the target nucleon (for odd-atomic-numbered nucleons) and dependent on mass (for even-atomic-numbered nucleons), both of which are present in the Sun with known abundances. Typical results from indirect dark matter searches in the Sun place limits on the scattering of dark matter with target nucleons, in a similar way with the results of direct searches. For the latest results see the limits achieved with 7 years of IceCube/DeepCore data [17], and limits obtained with a partial configuration of KM3NeT consisting of 6 detection lines over 433 days of operation [18].

4.2 Dark Matter Lines

Searching for a monochromatic energy emission (*line*) is one of the cleanest channels to frame the signature of dark matter annihilation or decay. These searches target the direct annihilation of two WIMPs into two neutrinos, transfering the center-of-mass energy of the initial state, roughly equivalent to $2\,M_{\rm WIMP}$, into kinetic energy of a neutrino pair. This search is challenged by the requirement of an excellent energy resolution alongside with a high statistics of data permitting to populate the differential energy region around the peak, but in turn is characterised by a very low background. Results obtained with 8 years of IceCube/DeepCore data are detailed in reference [19].

4.3 Dark Matter in Galactic Haloes

Cosmology indicates that galaxies form nested into large dark matter halos, responsible for the gravitational accumulation of matter [20]. The closest, largest dark matter reservoir is therefore the centre of the Milky Way. This region also hosts a large population of luminous sources, requiring particular techniques to observe it with γ-ray telescopes, but is directly accessible with neutrino telescopes. Telescopes in the Northern Earth Hemisphere, such as KM3NeT, have a good view of the Galactic Centre through the Earth filter in standard data taking mode. Telescopes in the South, such as IceCube, must resort to dedicated analysis techniques to veto atmospheric neutrinos without using the Earth filter. Recent results display upper limits on the dark matter annihilation rate based on the non-observation of a cluster of neutrino events from the centre of the Galaxy with KM3NeT [18] and IceCube [21].

4.4 Secluded Dark Matter

Provided that an incremented lifetime and exposure will soon hit the cosmological bound at $3 \cdot 10^{-26}{\rm cm}^3{\rm s}$, the dark matter parameter space might be extended to higher masses. However, classical WIMPs come to a halt at $\mathcal{O}(100)$ TeV due to a unitarity requirement. This can be evaded with a modified cosmology scenario in which dark-matter particles annihilate into an *on-shell* mediator, later decaying into Standard Model [22]. The relevant energy scale is not the heavy dark matter mass (that would demand a re- summation of electroweak radiation for $m_{\rm DM} > 10$ TeV), but rather the sub-TeV mediator mass, where the first order treatment of electroweak corrections included in PPPC4DMID [10] is under control. Upper limits when testing for the first time dark matter masses up to 6 PeV are detailed in reference [23]. In the hypothesis tested here, dark matter annihilates in two mediators in the centre of the Galaxy, to yield four Standard Model particles that leave the source already as final state neutrinos.

A different search scenario is the case of a vector mediator that propagates up to the vicinity of the detector, to then decay leaving a di-muon signature. This could be the case for close-by sources like the Sun, with the mediator escaping the Sun before producing any neutrinos, avoiding attenuation. Di-muon signature from the Sun was searched for in 6 years of IceCube data [24].

4.5 Heavy Dark Matter

Several scenarios foresee EeV-scale dark matter [25, 26]. As an example, right-handed neutrino $\nu_{R,1}$ in CPT symmetry, that decays into a Higgs and a light Majorana ν $\nu_{R,1} \rightarrow H + \nu_M$. This two-body process yields a ultra-high energy, monochromatic neutrino that would normally not make it through the Earth that results opaque at EeV energies. However, this channel would produce a visible signal when considering *tau* neutrinos and their regeneration that would shift the monochromatic, high energy line down to TeV-PeV energies. The ν_τ regeneration chain can be obtained with dedicated tools such as `taurunner` [27].

4.6 Light Boosted Dark Matter

Neutrino telescopes can test scenarios where a fraction of the dark matter population is relativistic (*boosted*). This can be realised in two ways: assuming that a certain amount of hot dark matter is initially present [28], or assuming that this is upscattered by interactions with cosmic rays [29]. Upscattering originates from the same dark matter-nucleus interactions as direct detection experiments search for; however, conventional direct detection experiments focusing on nuclear recoils are not sensitive to cold sub-GeV dark matter due to insufficient recoil energy. In either case, directionality is preserved suggesting to target the major reservoir at the Galactic Centre. In the first scenario, a sub-population of relativistic dark matter produced non-thermally in late-time processes. The search strategy is based on detecting Cherenkov light from the final state charged particles, above the Cherenkov threshold. As this foresees no ν yield, this is rather an unconventional usage of neutrino detectors. In the second scenario, upscattering originates from the same dark matter-nucleus interactions as direct detection experiments search for; however, conventional direct detection experiments focusing on nuclear recoils are not sensitive to cold sub-GeV dark matter due to insufficient recoil energy. For details of a search for boosted dark matter run with Super-Kamiokande see reference [30].

5 Conclusions

A dark matter candidate particle has been long searched for, with a crossfire strategy between direct searches for scattering of dark matter on baryons, production at colliders, and indirect searches looking at pair annihilation or decay products. Currently all these experimental efforts come to no avail. Neutrino telescopes are able to test particular scenarios where the majority of dark matter directly annihilates or decays to final state neutrinos. These instruments also benefit from being able to directly target the major dark matter reservoir at the centre of the Milky Way. Future strategies focus on extending the parameter space as well as incrementing the instrumental exposure, which might soon be able to exclude the entire WIMP parameter space.

Indirect searches assume a particle nature for dark matter, however this assumption is not essential. Alternative hypotheses identify dark matter with very massive, ordinary astrophysical objects (planets, dead stars, black holes), provided they do not emit radiation. Gravitational lensing set strong bounds on these scenarios. Also primordial black holes, baryonic but created before BBN, have been suggested as a dark matter candidate,but unlikely able to account for the totality of dark matter. Hardly testable through indirect searches are also other production mechanisms than freeze-out of a thermal relic: for instance *freeze-in* scenarios [31] or *darkogenesis* [32]. Meanwhile, the major and next generation neutrino observatories will continue towards pushing the thermal relic cross section. Dark matter searches remain a rich field of opportunities for novel scenarios considered the empty-handed WIMP search conducted until nowadays.

Acknowledgments

The author acknowledges the support from Generalitat Valenciana for Program GenT (ref. CIDEGENT/2021/023) and from MCIN for ASFAE/2022/023 with funding from the EU NextGenerationEU (PRTR-C17.I01).

References

[1] V.C. Rubin, J. Ford, W. Kent, Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions, **159**, 379 (1970). 10.1086/150317

[2] V.C. Rubin, Evidence for dark matter from rotation curves: Ten years later, AIP Conf. Proc. **222**, 371/380 (1991). https://doi.org/10.1063/1.40398

[3] F. Zwicky, Die Rotverschiebung von extragalaktischen Nebeln, Helvetica Physica Acta **6**, 110 (1933).

[4] E. Komatsu, J. Dunkley, M.R. Nolta, C.L. Bennett, B. Gold, G. Hinshaw, N. Jarosik, D. Larson, M. Limon, L. Page et al., Five-Year Wilkinson Microwave Anisotropy Probe Observations: Cosmological Interpretation, **180**, 330 (2009), `0803.0547`. 10.1088/0067-0049/180/2/330

[5] Planck Collaboration, Aghanim, N., Akrami, Y., Arroja, F., Ashdown, M., Aumont, J., Baccigalupi, C., Ballardini, M., Banday, A. J., Barreiro, R. B. et al., Planck 2018 results - i. overview and the cosmological legacy of planck, AA **641**, A1 (2020). 10.1051/0004-6361/201833880

[6] M. Cirelli, A. Strumia, J. Zupan, Dark matter (2024), `2406.01705`, `https://arxiv.org/abs/2406.01705`

[7] S. Adrián-Martínez et al., Letter of intent for KM3NeT 2.0, Journal of Physics G Nuclear Physics **43**, 084001 (2016), `1601.07459`. 10.1088/0954-3899/43/8/084001

[8] A. Achterberg, M. Ackermann, J. Adams, J. Ahrens, K. Andeen, D. Atlee, J. Baccus, J. Bahcall, X. Bai, B. Baret et al., First year performance of the icecube neutrino telescope, Astroparticle Physics **26**, 155 (2006). https://doi.org/10.1016/j.astropartphys.2006.06.007

[9] S. Navas, C. Amsler, T. Gutsche, C. Hanhart, J.J. Hernández-Rey, C. Lourenço, A. Masoni, M. Mikhasenko, R.E. Mitchell, C. Patrignani et al. (Particle Data Group Collaboration), Review of particle physics, Phys. Rev. D **110**, 030001 (2024). 10.1103/PhysRevD.110.030001

[10] M. Cirelli, G. Corcella, A. Hektor, G. Hütsi, M. Kadastik, P. Panci, M. Raidal, F. Sala, A. Strumia, Pppc 4 dm id: a poor particle physicist cookbook for dark matter indirect detection, Journal of Cosmology and Astroparticle Physics **2011**, 051–051 (2011). 10.1088/1475-7516/2011/03/051

[11] Q. Liu, J. Lazar, C.A. Argüelles, A. Kheirandish, aro: a tool for neutrino flux generation from wimps, Journal of Cosmology and Astroparticle Physics **2020**, 043 (2020). 10.1088/1475-7516/2020/10/043

[12] J.F. Navarro, C.S. Frenk, S.D.M. White, The Structure of cold dark matter halos, Astrophys. J. **462**, 563 (1996), `astro-ph/9508025`. 10.1086/177173

[13] A. Burkert, The Structure of Dark Matter Halos in Dwarf Galaxies, Astrophys. J. **447**, L25 (1995), `astro-ph/9504041`. 10.1086/309560

[14] C.A. Argüelles, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White, Dark matter decay to neutrinos, Phys. Rev. D **108**, 123021 (2023). 10.1103/PhysRevD.108.123021

[15] A. Albert, M. André, M. Anghinolfi, G. Anton, M. Ardid, J.J. Aubert, J. Aublin, B. Baret, S. Basa, B. Belhorma et al., Search for dark matter towards the galactic centre with 11 years of antares data, Physics Letters B **805**, 135439 (2020). https://doi.org/10.1016/j.physletb.2020.135439

[16] C. Arina, M.D. Mauro, N. Fornengo, J. Heisig, A. Jueid, R.R. de Austri, Cosmixs: cosmic messenger spectra for indirect dark matter searches, Journal of Cosmology and Astroparticle Physics **2024**, 035 (2024). 10.1088/1475-7516/2024/03/035

[17] R. Abbasi, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers, M. Ahrens, J.M. Alameddine, C. Alispach, A.A. Alves, N.M. Amin et al. (IceCube Collaboration), Search for gev-scale dark matter annihilation in the sun with icecube deepcore, Phys. Rev. D **105**, 062004 (2022). 10.1103/PhysRevD.105.062004

[18] K. Collaboration, S. Aiello, A. Albert, A.R. Alhebsi, M. Alshamsi, S.A. Garre, A. Ambrosone, F. Ameli, M. Andre, L. Aphecetche et al., First searches for dark matter with the km3net neutrino telescopes (2024), `2411.10092`, `https://arxiv.org/abs/2411.10092`

[19] R. Abbasi, M. Ackermann, J. Adams, S.K. Agarwalla, J.A. Aguilar, M. Ahlers, J.M. Alameddine, N.M. Amin, K. Andeen, G. Anton et al. (IceCube Collaboration), Search for neutrino lines from dark matter annihilation and decay with icecube, Phys. Rev. D **108**, 102004 (2023). 10.1103/PhysRevD.108.102004

[20] H. Mo, F. van den Bosch, S. White, Formation and Structure of Dark Matter Halos (Cambridge University Press, 2010), p. 319–365

[21] N. Chau, J.A. Aguilar, Indirect dark matter search in the galactic centre with icecube (2023), `2308.06729`, `https://arxiv.org/abs/2308.06729`

[22] M. Cirelli, Y. Gouttenoire, K. Petraki, F. Sala, Homeopathic dark matter, or how diluted heavy substances produce high energy cosmic rays, Journal of Cosmology and Astroparticle Physics **2019**, 014 (2019). 10.1088/1475-7516/2019/02/014

[23] T.A. collaboration, A. Albert, S. Alves, M. André, M. Anghinolfi, G. Anton, M. Ardid, S. Ardid, J.J. Aubert, J. Aublin et al., Search for secluded dark matter towards the galactic centre with the antares neutrino telescope, Journal of Cosmology and Astroparticle Physics **2022**, 028 (2022). 10.1088/1475-7516/2022/06/028

[24] C. Tönnis, Search for secluded dark matter with 6 years of icecube data (2021), `2107.10778`, `https://arxiv.org/abs/2107.10778`

[25] R. Aloisio, Pierre auger observatory and super heavy dark matter, EPJ Web of Conferences **280**, 07001 (2023). 10.1051/epjconf/202328007001

[26] L.A. Anchordoqui, C. Bérat, M.E. Bertaina, A. Castellina, O. Deligny, R. Engel, G.R. Farrar, P.L. Ghia, D. Hooper, O. Kalashev et al., Hunting super-heavy dark matter with ultra-high energy photons, Astroparticle Physics **132**, 102614 (2021). 10.1016/j.astropartphys.2021.102614

[27] I. Safa, J. Lazar, A. Pizzuto, O. Vasquez, C.A. Argüelles, J. Vandenbroucke, Taurunner: A public python program to propagate neutral and charged leptons, Computer Physics Communications **278**, 108422 (2022). https://doi.org/10.1016/j.cpc.2022.108422

[28] K. Agashe, Y. Cui, L. Necib, J. Thaler, (in)direct detection of boosted dark matter, Journal of Physics: Conference Series **718**, 042041 (2016). 10.1088/1742-6596/718/4/042041

[29] K. Abe, Y. Hayato, K. Hiraide, K. Ieki, M. Ikeda, J. Kameda, Y. Kanemura, R. Kaneshima, Y. Kashiwagi, Y. Kataoka et al. (Super-Kamiokande Collaboration), Search for cosmic-ray boosted sub-gev dark matter using recoil protons at super-kamiokande, Phys. Rev. Lett. **130**, 031802 (2023). 10.1103/PhysRevLett.130.031802

[30] K. Abe, Y. Hayato, K. Hiraide, K. Ieki, M. Ikeda, J. Kameda, Y. Kanemura, R. Kaneshima, Y. Kashiwagi, Y. Kataoka et al. (Super-Kamiokande Collaboration), Search for cosmic-ray boosted sub-gev dark matter using recoil protons at super-kamiokande, Phys. Rev. Lett. **130**, 031802 (2023). 10.1103/PhysRevLett.130.031802

[31] L.J. Hall, K. Jedamzik, J. March-Russell, S.M. West, Freeze-In Production of FIMP Dark Matter, JHEP **03**, 080 (2010), `0911.1120`. 10.1007/JHEP03(2010)080

[32] J. Shelton, K.M. Zurek, Darkogenesis: a baryon asymmetry from the dark matter sector, Physical Review D **82** (2010). 10.1103/physrevd.82.123512