

Reconstructing WIMP properties with neutrino detectors

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If the dark matter of the Universe is constituted by weakly interacting massive particles (WIMP), they would accumulate in the core of astrophysical objects as the Sun and annihilate into particles of the Standard Model. High-energy neutrinos would be produced in the annihilations, both directly and via the subsequent decay of leptons, quarks and bosons. While Čerenkov neutrino detectors/telescopes can only count the number of neutrinos above some threshold energy, we study how, by exploiting their energy resolution, large magnetized iron calorimeter and, possibly, liquid argon and totally active scintillator detectors, planned for future long baseline neutrino experiments, have the capability of reconstructing the neutrino spectrum and might provide information on the dark matter properties. In particular, for a given value of the WIMP mass, we show that a future iron calorimeter could break the degeneracy between the WIMP-proton cross section and the annihilation branching ratios, present for Čerenkov detectors, and constrain their values with good accuracy.

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INTRODUCTION

Cosmological and astrophysical observations provide growing evidence of the existence of Dark Matter (DM) in our Universe. One of the favored candidates is a weakly interacting massive particle (WIMP), a new stable neutral particle with typical mass in the 10 GeV–TeV range which interacts weakly [1]. These particles arise naturally in various extensions of the Standard Model of Particle Interactions (SM), e.g. the lightest neutralino in supersymmetric models with R-parity conservation [1], stable scalars in little Higgs models [2], the lightest Kaluza-Klein excitation of the SM fields in models with universal extra-dimensions [3]. Direct searches for WIMPs look for the recoil energy of nuclei due to interactions with the DM particles passing through the Earth [4]. WIMP signatures can also be found indirectly, namely by observing gamma-rays, positrons, anti-protons and neutrinos produced in dark matter annihilations [1]. As the annihilation rate scales with the square of the dark matter density, indirect signals are expected to be stronger where DM accumulates, as, for instance, the galactic center and astrophysical bodies. High-energy neutrinos are produced in the annihilation either directly or by subsequent decay of SM fermions and bosons [5] and their spectrum could provide information on the WIMP mass, the WIMP-proton cross section and the branching ratios of the various annihilation channels, and hence, on the DM properties.

Searches for high energy neutrinos can be performed in Čerenkov neutrino detectors/telescopes [6, 7], as Super-Kamiokande (SK), AMANDA, IceCube, but no positive

evidence has been found so far. However, these detectors are unable to fully reconstruct the neutrino energy and therefore cannot provide information on the neutrino spectrum. In the case of small detectors with large photomultiplier coverage, like SK, the size limits the maximum energy for which the events are contained, so only through-going muons are of interest for energies of tens of GeV or higher. In the case of neutrino telescopes like IceCube, least granular, the size limits the energy threshold for detection. In both cases and for the energies of interest, these detectors can only count neutrinos above their energy threshold. On the other hand, different conceptual designs for detectors for future neutrino long baseline experiments show that Magnetized Iron Calorimeter Detectors (MIND) [8], or its variants as MONOLITH [9] or INO [10], Liquid Argon Time Projection Chambers (LArTPC) [11] and Totally Active Scintillator Detectors (TASD) [12] are able to measure the energy and direction of the initial neutrino with good precision at energies of tens of GeVs.

In the present letter, we restrict our analysis to MIND, which are conceptually similar to the existing MINOS detector [13] but with a mass one order of magnitude larger. Due to its ability for a precise muon charge discrimination, they have been proposed as ideal detectors for future neutrino factories. For the same reason, these detectors have also been considered as atmospheric neutrino observatories, opening up the possibility of determining the neutrino mass hierarchy and the small mixing angle θ_{13} , due to matter effects in the oscillations of upward-going atmospheric neutrinos [14]. Here, we reveal a novel aspect of MIND [15], showing that they might constitute excellent observatories to detect neutrinos from WIMP

annihilations. For a given value of the WIMP mass, we study the neutrino signal from WIMP annihilations in these detectors, and exploit their energy and angular resolution in order to reconstruct the neutrino spectrum and, ultimately, to study DM properties [16]. By measuring the branching ratios of annihilation into different channels and the WIMP-proton cross section, these measurements could provide a unique opportunity for getting information on the WIMP couplings with the particles of the SM.

NEUTRINOS FROM WIMPS ANNIHILATIONS

When a WIMP goes through a celestial body, as the Sun, it might interact elastically with the nuclei and get scattered to a velocity smaller than the escape velocity, remaining gravitationally trapped in the body. It will then undergo additional scatterings, settling in the Sun core, giving raise to an isothermal distribution. The WIMPs so accumulated can annihilate with other WIMPs into SM particles, as quarks, leptons and, if kinematically allowed, gauge and Higgs bosons. Typically in the Sun, for sufficiently high capture rate and annihilation cross section, equilibrium is reached and the annihilation rate Γ_{ann} is related to the capture rate C_{\odot} as $\Gamma_{\text{ann}} = 1/2C_{\odot}$, which, for the Sun, is given by [17]

$$C_{\odot} \simeq 9 \times 10^{24} \text{ s}^{-1} \left(\frac{\rho_{\text{local}}}{0.3 \text{ GeV/cm}^3} \right) \left(\frac{270 \text{ km/s}}{\bar{v}_{\text{local}}} \right)^3 \times \left(\frac{\sigma}{10^{-2} \text{ pb}} \right) \left(\frac{50 \text{ GeV}}{m_{\text{DM}}} \right)^2, \quad (1)$$

where ρ_{local} is the local WIMPs density, \bar{v}_{local} is the velocity dispersion of WIMPs in the halo, σ is the WIMP-proton cross section, and m_{DM} is the WIMP mass. The capture rate can be different by several orders of magnitude for spin-dependent and spin-independent interactions. Typically, for most neutralino models as well as for Kaluza-Klein DM, the spin-dependent cross-section dominates over the spin-independent one. The opposite happens for scalar WIMPs. These scattering cross sections are constrained in direct DM searches [18], which put very strong bounds on the spin-independent ones. Since, in the Earth, the abundance of nuclei with odd mass number is extremely small, the neutrino flux from WIMP annihilations is strongly constrained by the bounds on the spin-independent cross section and would be too low to be interesting for detection in MIND, LArTPC or TAsD. Thus, for our purposes we will focus on WIMP annihilations in the Sun, for which the much more weakly constrained spin-dependent cross section may play the dominant role.

High-energy neutrinos would be produced directly or indirectly via the decay of other products of the annihilations [1]. A broad spectrum of neutrinos is so generated

and depends on the WIMP mass and on the branching ratios into the various channels:

$$\frac{dN_{\nu}}{d\Omega dt dE_{\nu}} = \frac{\Gamma_{\text{ann}}}{4\pi R^2} \sum_i \text{BR}_i \frac{dN_i}{dE_{\nu}}, \quad (2)$$

where the sum includes the possible annihilation channels with spectrum dN_i/dE_{ν} and branching ratio BR_i , and R is the Sun-Earth distance. If the DM is a Majorana fermion, the annihilation amplitude into fermion pairs is proportional to the fermion mass, so that the neutrino channel is irrelevant and annihilations are dominated by heavy fermions, bs , τs , cs and, if kinematically allowed, ts . Neutralinos can annihilate into fermions as well as gauge bosons and Higgs and the dominant channels are controlled by the neutralino composition [1]. Typically, for neutralinos lighter than the W boson, the annihilation into $b\bar{b}$ pairs gives the main contribution, with harder neutrinos from $\tau\bar{\tau}$. For higher masses, the gauge bosons channels are allowed and can have the highest branching ratio. Kaluza-Klein WIMPs can annihilate directly into neutrinos [3] with a branching ratio of few per cent and would provide a specific signature with a peak in the neutrino spectrum at $E_{\nu} = m_{\text{DM}}$. Their main annihilation channels are charged leptons and light quarks with the neutrino flux generated dominantly by the $\tau\bar{\tau}$ mode. In the following, we will treat the branching ratios as free parameters as their exact values depend on the type of particle considered and on its couplings.

Annihilations into τ 's and gauge bosons produce a hard spectrum which peaks around $0.4 m_{\text{DM}}$ ($0.5 m_{\text{DM}}$) for $\nu_{e,\mu}$ (ν_{τ}) for the former channel and even at higher energies for the latter [19]. Quarks hadronize producing a large number of mesons and baryons which subsequently decay producing a softer neutrino spectrum. For instance, neutrinos from bs and cs have a spectrum which peaks at energies $\sim 0.15 m_{\text{DM}}$ or lower, depending on the WIMP mass, and drops to zero around $E_{\nu} \sim (0.6-0.7) m_{\text{DM}}$ [19]. Light quarks hadronize mostly in pions which, as muons, get stopped before decaying and therefore produce only low energy neutrinos. Once produced, neutrinos propagate in the Sun, being absorbed via charged-current interactions and losing energy due to neutral-current ones. These effects, in addition to neutrino oscillations between different flavors, need to be taken into account [19].

RECONSTRUCTING DM PROPERTIES

High-energy neutrinos can be detected in neutrino detectors and stringent bounds have already been set [6] and will be further improved by neutrino telescopes [7]. However, as these experiments cannot reconstruct the neutrino energy, they can only provide limited information on the neutrino spectrum. In order to reconstruct the *neutrino spectrum*, the analysis presented here exploits the *energy and angular resolution* of MIND, which

allow not only to measure precisely the energy and direction of muons produced by the charged current interactions (CC) of ν_μ and $\bar{\nu}_\mu$ but possibly also the energy of the electrons [8, 20], produced by ν_e ($\bar{\nu}_e$) interactions. In addition, these detectors will be able to reconstruct the energy and angle of the hadron shower, so that a good energy and direction resolution for the incoming neutrino will be achieved. We show that the degeneracy among different parameters can be broken by using the muon and electron energy spectra. In particular, a larger annihilation rate Γ_{ann} could always be traded by a smaller branching ratio to a hard channel ($\tau^+\tau^-$) in absence of information on the spectrum.

In the following we will consider a light WIMP candidate with $m_{\text{DM}} < 80$ GeV and therefore, we will focus on its dominant annihilation modes for these masses, i.e., $\tau^+\tau^-$ (hard) and $b\bar{b}$ (soft) channels. Note that the contribution from $c\bar{c}$ is similar to the one of $b\bar{b}$ but with a lower normalization [19]. This technique might not be competitive with neutrino observatories (AMANDA and Icecube) for WIMP masses $\gtrsim 100$ GeV, since the typical sizes of future MIND, LArTPC and T ASD might not allow a precise measurement of high lepton energies. However, it should be noted that, even for high WIMP masses, these detectors could be useful for detecting the low energy tail of the neutrino spectrum [23]. In our study we assume the mass of the WIMP to be known and, for definiteness, we take $m_{\text{DM}} = 50$ GeV and 70 GeV.

Let us now comment on our assumption of taking a given value for the WIMP mass. By the time the detectors discussed in the present article are available, information on the WIMP mass might be already available from the LHC (Large Hadron Collider) and, possibly, a future ILC (International Linear Collider) as well as direct and indirect dark matter searches. With the start of LHC in 2008, the neutral WIMP candidate for the dark matter can be indirectly detected in an event looking for missing energy and missing transverse momentum. By a detailed determination of the kinematics of the quarks and leptons, typically it might be possible to measure the WIMP mass with a 10% accuracy (see, e.g., Ref. [24]). The prospected error depends strongly on the model of physics beyond the SM and the values of the parameters. For example, for the SPS1a benchmark point, the LSP mass could be determined to be $m_{\text{DM}} = (96 \pm 5)$ GeV at the LHC and $m_{\text{DM}} = (96 \pm 0.05)$ GeV at the ILC [24]. For less favorable points in the parameter space, worse accuracies will be reachable. The value for the mass determined in collider searches could be used as input in our analysis, assuming that the observed WIMP corresponds to the dark matter particle.

A model-independent determination of the WIMP dark matter mass could also be obtained in direct DM searches which look for the nuclear recoil in an interaction between a WIMP and a nucleus in the detector [25]. The recoil spectrum is strongly mass-dependent

if $m_{\text{DM}} < 100$ GeV². For instance, a superCDMS-like experiment, with exposures of 3×10^3 (3×10^4) [3×10^5] kg days and a spin-independent cross section close to the present bound $\sigma_{\text{SI}} = 10^{-7}$ pb, would be able to measure a light WIMP mass with an accuracy of $\sim 25\%$ (15%) [2.5%] [26]. Similar conclusions can be drawn for the case of spin-dependent cross sections with comparable statistics. Nevertheless, these measurements are affected by the uncertainties in the WIMP velocity distribution and in the local WIMP distribution. A method which is independent of the WIMP density and of the WIMP-nucleon cross section has been also proposed [27]. By comparing the recoil energy spectrum in direct searches which use different detector materials, it is found that a WIMP mass smaller than 50 GeV can be determined with a 1- σ error of 20% if a total statistics of 500 events is available [27].

Information on the WIMP mass could also be found from indirect dark matter searches. Some information on the WIMP mass could also be obtained from the angular distribution of neutrino-induced muons in large water-Čerenkov detectors [28]. On the other hand, as the WIMP density in the center of galaxies is predicted to be enhanced, a high rate of WIMP annihilation are expected and produce sizable fluxes of SM particles, as neutrinos, photons, quarks and leptons. High energy photons can be produced either directly or via the hadronic interactions in the interstellar medium. In the first case, the gamma spectrum presents a very clear signature with a peak at the WIMP mass, allowing its precise determination. In the case of gamma-rays from primary hadrons, the spectrum has a sharp energy cut-off in correspondence with m_{DM} . It has been estimated that GLAST could constrain the WIMP mass at the 25% level, for $m_{\text{DM}} = 100$ GeV, and future Imaging Atmospheric Čerenkov Telescopes, with sufficiently small energy threshold, could detect the peak from direct annihilation into photons [29].

In addition, the energy information in the WIMP neutrino signal in the detectors considered in the present article could allow, in principle, to infer directly the WIMP mass by exploiting the cutoff in the spectra. Since the typical sizes of future MIND, LArTPC and T ASD might not allow to have sufficient statistics at the tail of the spectrum, this measurement could be very challenging. A detailed analysis needs to be performed, but it is beyond the scope of the present study [23].

We have computed the number of electron and muon neutrino-induced CC events for $m_{\text{DM}} = 50$ and 70 GeV, by using the evolved neutrino spectra from Ref. [19]. We have, conservatively, considered nine energy bins (5 GeV bins from an energy of 5 GeV for $m_{\text{DM}} = 50$ GeV and 7 GeV bins from an energy of 7 GeV for $m_{\text{DM}} = 70$ GeV), where the low energy cut is adopted to avoid the atmospheric neutrino background. With good statistics, the precision in the measurement of m_{DM} , for $m_{\text{DM}} \gtrsim 50$ GeV, depends on the muon energy resolution of MIND

at energies $E_\nu \sim 50 - 100$ GeV, expected to be $\sim 5 - 8\%$ at 50 GeV and slightly worse for higher energies [20].

For an ideal detector with perfect lepton angular resolution, the atmospheric neutrino background would be reduced to the fraction of events within the angular size of the Sun ($\sim 6.7 \times 10^{-5}$ sr). However, the lepton does not travel in the same direction as the incident neutrino except when averaged over many events. We conservatively take the root mean square (rms) spread in direction between the incident neutrino and the lepton (in radians) as

$$\theta_{\text{rms}} \simeq \sqrt{\frac{1 \text{ GeV}}{E_\nu}}, \quad (3)$$

where E_ν is the energy of the incoming neutrino. Therefore, a very conservative approach is to sum over the atmospheric neutrino background contributions within a region of opening angle θ_{rms} .

The expected number of muon (electron) neutrino-induced events in the i -th bin is computed as a function of the WIMP-proton scattering cross section and of the branching ratios into b^+b^- (soft channel) and $\tau^+\tau^-$ (hard channel),

$$N_{i,\mu(e)} = N_T t \int_{E_i}^{E_i+\Delta} dE_\nu \int d\theta \left(\phi_{\nu_\mu(\nu_e)}(E_\nu) \sigma_{\nu_\mu(\nu_e)}^{\text{CC}}(E_\nu) + \phi_{\bar{\nu}_\mu(\bar{\nu}_e)}(E_\nu) \sigma_{\bar{\nu}_\mu(\bar{\nu}_e)}^{\text{CC}}(E_\nu) \right) \times \frac{V_{\mu(e)}}{V_{\text{det}}}, \quad (4)$$

where Δ is the energy bin width, θ is the angle which measures the relative position of the Sun with respect to the detector location, N_T is the number of available targets, V_{det} is the total volume of the detector, t is the exposure time, ϕ is the evolved (anti)neutrino spectra, σ^{CC} is the CC (anti)neutrino cross section and $V_{\mu,e}$ is the volume of detector available for the neutrino to interact. For electron-like events, which are all contained, this fiducial volume V_e is simply the detector volume V_{det} . For muon-like contained-events, it depends on the detector geometry and on the muon range in iron $R_\mu(E_\mu)$. For a detector with cylindrical shape, it is given by [21]

$$V_\mu(E_\mu, \theta) = 2hr^2 \arcsin \left(\sqrt{1 - \frac{R_\mu^2(E_\mu)}{4r^2} \sin^2 \theta} \right) \times \left(1 - \frac{R_\mu(E_\mu)}{h} |\cos \theta| \right), \quad (5)$$

where $r = 13$ m and $h = 20$ m are the detector radius and height we have considered. We approximate the muon energy by its averaged value, which for the energy range of interest is $\langle E_\mu \rangle = 0.48 E_\nu$ [22]. Also notice that the volume of detector available is a function of the azimuthal angle θ , which varies from 0 to π in 12 hours. Thus, for the assumed geometry, the effective volume will be maximal when the Sun is at the horizon. On the other hand, if

a good energy resolution is achieved up to some energies even for partially-contained events (by means of using the bending of the muon trajectory due to the magnetic field), the fiducial volume to be considered is V_{det} . We will consider both cases, when partially-contained muon-like events are not included in the analysis and when all muon-like events with the interaction vertex in the detector contribute.

The expected number of muon and electron neutrino-induced events is then fitted performing a χ^2 analysis. We define

$$\chi_{\mu^\pm + e^\pm}^2 = \sum_{\alpha, \alpha' = \mu, e} \sum_{i, j} (n_{i,\alpha} - N_{i,\alpha}) C_{i,\alpha'; j, \alpha'}^{-1} (n_{j,\alpha'} - N_{j,\alpha'}), \quad (6)$$

where C is the covariance matrix and only statistical errors, being the dominant ones, have been considered. $N_{i,\alpha}$ is given by Eq. (4) and $n_{i,\alpha}$ represents the simulated muon (electron) data taking into account the total muon or electron atmospheric neutrino background within the i -th energy bin and integrated over a solid angle $\Delta\Omega = 2\pi\theta_{\text{rms}}$, and is given by

$$n_{i,\alpha} = \text{Smear}(N_{i,\alpha} + N_{i,\text{atmos}}) - N_{i,\text{atmos}}, \quad (7)$$

where the function Smear indicates that Gaussian or Poisson smearing has been applied following the Monte Carlo techniques of Ref. [30] to mimic the statistical uncertainty.

In Figs. 1 and 2, we illustrate the simultaneous extraction of the scattering cross section of the WIMP off a proton and the branching ratio into $\tau^+\tau^-$ assuming a 50 kton MIND with the geometry described above. In Fig. 1 we consider the case of a WIMP mass of $m_{\text{DM}} = 50$ GeV and the input simulated values are $\sigma = 7 \times 10^{-3}$ pb and $\text{BR}_{\tau^+\tau^-} = 20\%$. We have assumed 15 years of data taking and have only included electron-like and contained muon-like events. The dotted-dashed red lines depict the 90% confidence level (CL) contours assuming that no energy information is available: as previously anticipated, a larger annihilation rate could always be mimicked by a lower branching ratio into $\tau^+\tau^-$. Notice that there will be a continuous region of degenerate solutions, implying the impossibility of extracting either the different branching ratios or the WIMP-proton scattering cross section. In this scenario, the measurement of the WIMP mass is of course out of reach. Instead, if we now include the information on the neutrino energy spectrum, we obtain the 90% CL contours depicted by the solid blue line. The strong correlation between σ and $\text{BR}_{\tau^+\tau^-}$ (or $\text{BR}_{b^+b^-}$) is broken. The reason is simple: the differential neutrino spectrum for each possible annihilation channel (hard or soft) has a characteristic shape, different from one channel to another. For this case, $m_{\text{DM}} = 50$ GeV, the spectrum for $b\bar{b}$ peaks at ~ 7 GeV and represents roughly 20% of that of $\tau^+\tau^-$, peaked at ~ 20 GeV. We also illustrate the results for the ideal case for which the atmospheric neutrino background only contributes within the

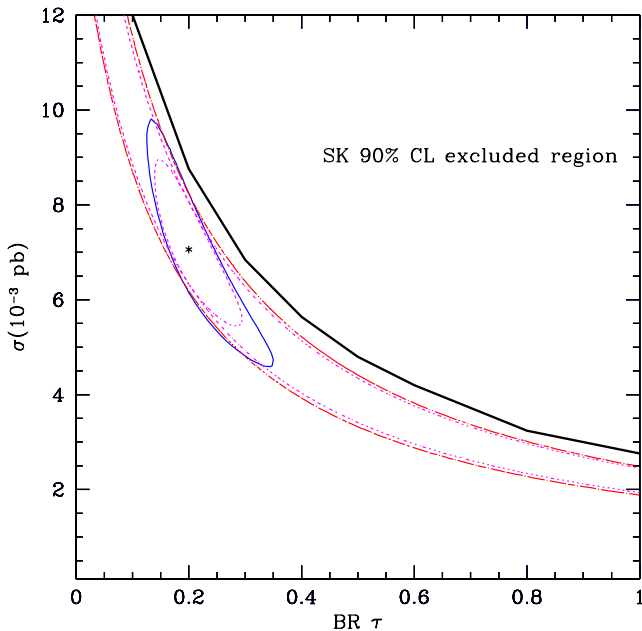


FIG. 1: The solid blue (dotted-dashed red) contours denote the 90% CL limits, for 2 degrees of freedom, for the simultaneous extraction of the WIMP-proton cross section and the annihilation branching ratio into the $\tau^+\tau^-$ channel with (without) energy information by using only fully-contained events with an exposure of $750 \text{ kton} \cdot \text{yrs}$ (see text for details). The simulated nature values are $m_{\text{DM}} = 50 \text{ GeV}$, $\sigma = 7 \times 10^{-3} \text{ pb}$ and $\text{BR}_{\tau^+\tau^-} = 20\%$. The dashed magenta lines (inner contours) illustrate the case (for 90% CL) in which the atmospheric neutrino background is integrated only over the real size of the Sun. We also show the 90% CL excluded region by SK [6].

real angular size of the Sun (dashed magenta lines). As can be seen, by considering a more detailed and realistic expression for the angular resolution than that given by Eq. (3), our results would not be significantly improved. In Fig. 2 we show the 90% CL contours for 15 years for $m_{\text{DM}} = 70 \text{ GeV}$ with the input simulated values $\sigma = 5 \times 10^{-3} \text{ pb}$ and $\text{BR}_{\tau^+\tau^-} = 10\%$. The solid blue line represents the case when partially-contained muon-like events are not considered, whereas the inner dotted magenta line depicts the case when we also include this type of events to perform the analysis. In this figure, we have considered the atmospheric neutrino background integrated over a half-cone aperture given by Eq. (3). It is important to note that by adding the partially-contained events, in order to achieve the same results as for the case of only contained events, the total number of years could be reduced from 15 to 10 years of data taking, the minimum running time of these detectors in the context of neutrino factories. In both figures, the equivalent 90% CL SK limit [6] is included.

As both figures show, for these relatively low WIMP masses and large spin-dependent cross sections, the determination of the annihilation branching ratios and

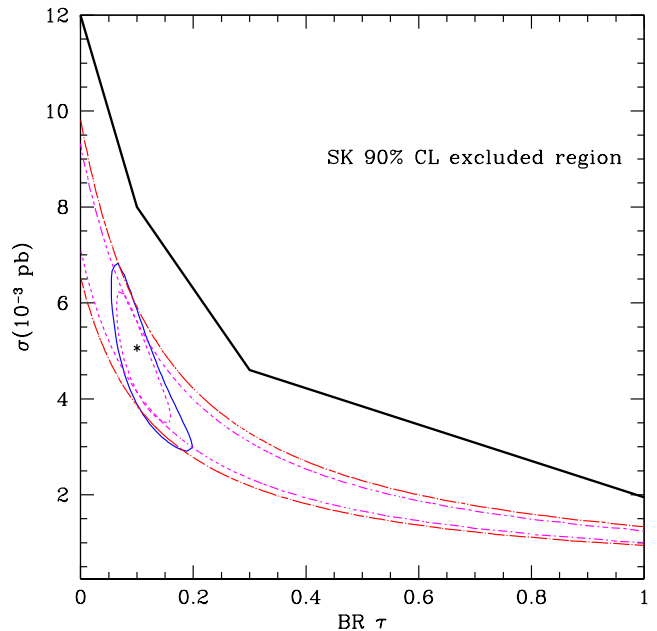


FIG. 2: The solid blue (dotted-dashed red) contours denote the 90% CL limits, for 2 degrees of freedom, for the simultaneous extraction of the WIMP-proton cross section and the annihilation branching ratio into the $\tau^+\tau^-$ channel with (without) energy information by using only fully-contained events with an exposure of $750 \text{ kton} \cdot \text{yrs}$ (see text for details). The simulated nature values are $m_{\text{DM}} = 70 \text{ GeV}$, $\sigma = 5 \times 10^{-3} \text{ pb}$ and $\text{BR}_{\tau^+\tau^-} = 10\%$. The dashed magenta lines (inner contours) illustrate the case (for 90% CL) in which partially-contained events are also included in the analysis. We also show the 90% CL excluded region by SK [6].

WIMP-proton cross section could be achieved. Notice that a positive signal of neutrinos from WIMP annihilations in the Sun in these detectors will immediately point to a spin-dependent cross section. In LArTPC and TASD similar results could be obtained. In fact, we have checked that considering only the ν_μ or the ν_e signal does not modify the results substantially, a part from a small change due to the smaller atmospheric neutrino background for ν_e . A detailed analysis for different WIMP masses and type of detectors is in preparation [23].

CONCLUSIONS

Searches of high-energy neutrinos from WIMP annihilations in the Sun could constitute a powerful probe of WIMP properties. While the total neutrino flux is controlled by the annihilation rate (proportional to the WIMP-proton cross section), the shape of the neutrino spectrum depends on the WIMP mass and on the branching ratios of different channels. Čerenkov neutrino detectors/telescopes are counting experiments and can only provide limited information. On the contrary, we have

shown that, by exploiting the good energy and angular resolution at energies of tens of GeV, future MIND, LArTPC and TASP could have the capability to reconstruct the neutrino spectrum, and could provide important information on the WIMP mass, its annihilation branching ratios and WIMP-proton cross section. In particular, our analysis shows that, for a given value of the WIMP mass, the degeneracy between the WIMP-proton cross section and the branching ratios into soft and hard channels could be broken and important information on the WIMP dark matter couplings might be obtained. This information should be combined with the constraints and measurements from direct and indirect DM searches to probe the nature and properties of DM particles and to test that the WIMP candidate found in collider searches does indeed constitute the observed dark matter of the Universe.

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