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Determining the dark matter mass with DeepCore

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Cosmological and astrophysical observations provide increasing evidence of the existence of dark matter in our Universe. Dark matter particles with a mass above a few GeV can be captured by the Sun, accumulate in the core, annihilate, and produce high energy neutrinos either directly or by subsequent decays of Standard Model particles. We investigate the prospects for indirect dark matter detection in the IceCube/DeepCore neutrino telescope and its capabilities to determine the dark matter mass.

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Introduction.— Establishing the particle identity of the dark matter (DM) of the Universe is one of the fundamental questions which needs to be addressed in modern physics [1]. One of the currently favored candidates is a weakly interacting massive particle (WIMP), a stable neutral particle with a mass in the GeV–TeV range, which is predicted in many extensions of the Standard Model of particle physics (SM).

The DM particle properties might be tested in direct and indirect searches and in collider experiments. Direct searches look for the recoil of nuclei due to WIMPs passing through the detector and are sensitive to the spin-dependent WIMP-proton (-neutron) cross section, $\sigma_{\rm SD}^{\rm p(n)}$, and the spin-independent one, $\sigma_{\rm SI}$. Indirect searches focus on the products of DM annihilations (or decays), such as gamma-rays, positrons, anti-protons and neutrinos, in regions where the DM density is expected to be high, such as the center of the Milky Way, dwarf galaxies, clusters of galaxies, etc. Colliders could produce DM particles and make possible the study of their properties. In addition to each individual search, their combination is crucial in constraining DM properties [2–6]. In particular, the determination of the DM mass is of great theoretical importance in order to establish the DM particle identity but it is a challenging task.

One of the astrophysical objects of particular interest for indirect searches is the Sun as a high DM density could be present: DM particles, traversing it, can get scattered to velocities lower than the escape velocity and be captured. The annihilations of these DM particles would give rise to a neutrino flux, which is produced either directly or indirectly via the decay of other products of the annihilations. Depending on the annihilation channel, the neutrino energy is different: neutrinos from particles which decay very fast have typically high energies and longer lived particles, such as muons and light quarks, significantly loose energy before decaying and produce softer neutrinos [2]. Therefore, the neutrino spectrum depends on several DM properties, such as its mass, the DM-nucleon cross section and the branching ratios for the various possible annihilation channels.

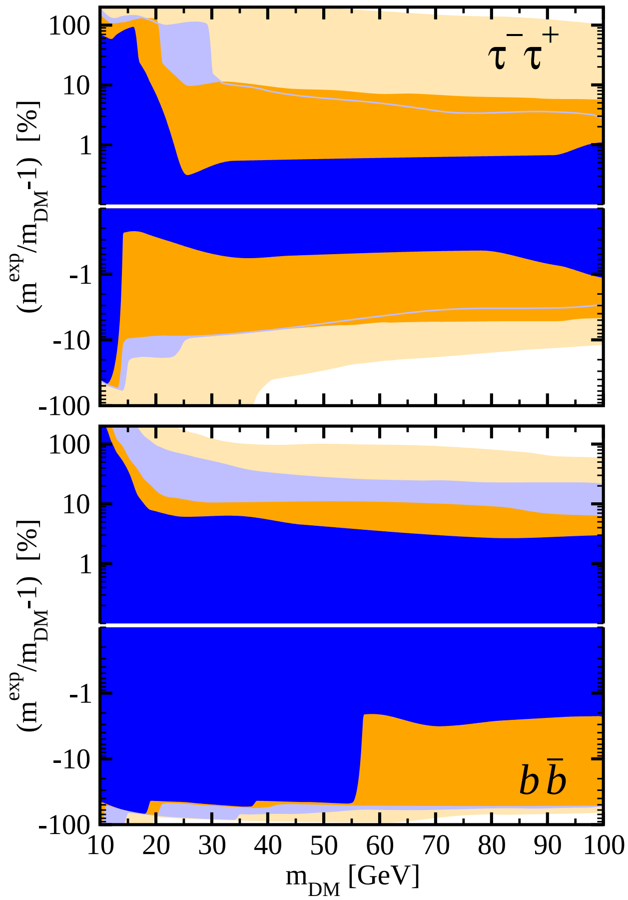

Figure 1: ***Relative error in the DM mass after 10 years at DeepCore at 90% CL***, *with (light colors) and without (dark colors) systematic errors. Top panel: Annihilations into $\tau^-\tau^+$ with $\sigma_{\rm SD}^{\rm p} = 10^{-3}$ pb (blue), 10^{-4} pb (orange). Bottom panel: Annihilations into $b\bar{b}$ with $\sigma_{\rm SD}^{\rm p} = 10^{-2}$ pb (blue), 4×10^{-3} pb (orange).*

Indirect searches, detecting these neutrinos and reconstructing their spectrum, are sensitive to the neutrino mass [2]. It has been shown that future large neutrino detectors with good energy resolution, such as magnetized iron detectors, could measure the *neutrino* spectrum [7, 8]. However, so far, no simulation of this effect in a neutrino telescope has been performed. These very large detectors cannot fully reconstruct the neutrino energy but measure the *neutrino-induced* muon spectrum, which is strongly correlated with the neutrino one. Here, we show for the first time (see Fig. 1) that, by studying the neutrino-induced muon energy spectrum, the DeepCore Array [9], a huge compact Čerenkov detector located at the bottom center of the IceCube Neutrino Telescope, could reach an excellent precision in determining the DM mass. This detector extends the IceCube neutrino detection capabilities to neutrino energies as low as 10 GeV allowing to study low mass WIMPs with a detector with a huge effective volume, $\mathcal{O}(10)$ Mton.

Neutrinos from WIMPs annihilations in the Sun.— When a DM particle with a mass above a few GeV passes through the Sun, it might interact elastically with the nuclei and get scattered to a velocity smaller than the escape velocity, remaining gravitationally trapped. Then it undergoes additional scatterings, settling in the Sun core, giving rise to an isothermal distribution. For sufficiently high capture rate and annihilation cross section, equilibrium is reached and the annihilation rate $\Gamma_{\rm ann}$ is related to the capture rate $C_\odot$ as [7, 10]

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

where $\rho_{\rm local}$ is the local DM density, $\bar{v}_{\rm local}$ is the DM velocity dispersion in the halo and σ is the DM-nucleon cross section. The spin-independent scattering cross section is very strongly constrained by direct searches [11] and hence, at the energies of interest, only signals due to a large spin-dependent cross section could be tested with neutrino telescopes. In many extensions of the SM the spin-dependent cross section can dominate, even by several orders of magnitude [12]. The current most stringent bounds on the WIMP-proton elastic scattering cross section, $\sigma_{\rm SD}^{\rm p}$, are provided by the SIMPLE experiment [13], whose Stage 1 and 2 combined results (only Stage 1 revised results) yield a lower limit with a minimum of $\sigma_{\rm SD}^{\rm p} < 4.2\,(8.3) \times 10^{-3}$ pb at $m_{\rm DM} = 35$ GeV. This limit is already competitive with the indirect ones obtained from the non-observation of neutrinos from DM annihilations in the Sun at the Super-Kamiokande detector [14, 15].

The DM accumulated in the Sun can annihilate into SM particles. Nevertheless, due to the absorption in the solar matter, among all the SM products of annihilations, only neutrinos can escape. Neutrinos could be produced either directly or after the hadronization, fragmentation and decay of the SM particles in the final states. A broad spectrum of neutrinos arises and depends on the DM mass and on the branching ratios into the various channels:

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

where the sum includes the possible annihilation channels with spectrum dN_i/dE_ν and branching ratio ${\rm BR}_i$, and R is the Sun-Earth distance. The annihilation channels can be distinguished into *hard channels* producing highly energetic neutrinos, typically due to fast-decaying SM particles and *soft channels*, which are due to SM particles which interact significantly with the high density background in the Sun loosing significant amounts of energy before decaying [2, 16, 17]. As our benchmark channels, we consider annihilations into τ pairs for the hard case and into b quarks for the soft one.

Once produced in the core of the Sun after DM annihilations, neutrinos propagate undergoing neutrino oscillations, absorption due to neutral and charged current interactions, loss of energy due to neutral current and regeneration, when τ leptons produced in the interactions decay into secondary lower energy neutrinos [2, 16, 17]. In order to simulate the WIMP signal at the detector, including all the above effects, we use the publicly available code `WimpSim` [16].

Neutrino detection in DeepCore.— The main idea of the present letter is to study the neutrino-induced muon energy spectrum in order to gain information on the DM properties, and in particular about the DM mass. Using neutrinos from DM annihilations in the Sun to constrain DM properties has been considered in different contexts [2, 5, 7, 8]. Here, we focus for the first time on the capabilities of the DeepCore Array for low mass WIMPs.

DeepCore [9] is located at the bottom center of the IceCube detector at a depth between 2100 m and 2450 m, avoiding a horizontal layer of poor optical properties due to a high content of dust. The detector has a higher instrumentation density with 6 additional strings instrumented with phototubes with higher quantum efficiency with respect to IceCube. The same phototubes are used for the IceCube strings in the same volume. The advantages of DeepCore are multiple. The ice at this depth is on average twice as clear as the one above allowing to detect a larger number of unscattered photons and to achieve a better pattern recognition and low energy neutrino reconstruction. The higher vertical density of photosensors, 7 m instead of 17 m for IceCube, and the higher quantum efficiency lead to a significant gain in sensitivity, up to a factor of 6, especially for low energy neutrinos. Finally, the remaining volume of the IceCube detector together with a horizontal region with additional instrumentation at a depth of 1750 m – 1850 m can be used as an active veto for downgoing atmospheric muons, significantly reducing this dominant background.

Due to the lack of angular resolution for cascade events, in this work we only consider muon-like events (upgoing and downgoing), with an effective volume for the 86-string configuration (IC86) at trigger (SMT3) and online filter level $V_{\rm eff} \simeq 8$ Mton at $E_\nu \simeq 10 - 12$ GeV and $V_{\rm eff} \simeq 45$ Mton at $E_\nu \simeq 100 - 200$ GeV [18]. It is important to note that this estimate of the effective volume does not include analysis or reconstruction efficiencies. The IceCube Collaboration aims to maintain a signal efficiency of well over 50% for contained and partially contained events [9], which we approximately account for by scaling down the simulated events by a factor of 2. For muon-like events, the angular resolution of the detector is expected to be much better than the average angle between the incoming neutrino and the produced muon. Hence, the Sun is basically a point source for this detector at these energies and we consider the atmospheric neutrino background integrated over a half-cone aperture given by $\theta_{\rm rms} = \sqrt{\frac{1~{\rm GeV}}{E_\nu}}$. As for the energy resolution, it has not been estimated yet, but it will rely on track length rather than track brightness. Assuming the track estimation to be good to 50 meters, we consider bins with a 10 GeV width in the muon energy. We assume 10 years of data taking.

In these searches, the main source of background is due to atmospheric neutrinos. In the energy region of interest, the absolute atmospheric neutrino fluxes are known within ~10%-20%, the major contributors coming from hadron production and the primary cosmic ray fluxes [19]. We note, though, that this uncertainty could be substantially reduced [14]. However, other sources of systematic errors, such as the astrophysical uncertainties in the calculation of the capture rate, could also affect the results [20]. All in all, we add an overall 15% systematic error in our computations as a conservative assumption.

Determination of the DM mass in DeepCore.— In Fig. 2, we show the sensitivity to DM annihilation in the Sun due to elastic spin-dependent interactions off protons at 90% confidence level (CL). We show the results for the $\tau^-\tau^+$ (hard) and $b\bar{b}$ (soft) annihilation channels. For comparison, we also show the recent results from the direct searches by the SIMPLE experiment [13] and those using Super-Kamiokande data [14, 15]. It is important to note that the results of these latter analyses do not include systematic errors of the kind mentioned above, so should be compared with our solid lines in Fig. 2.

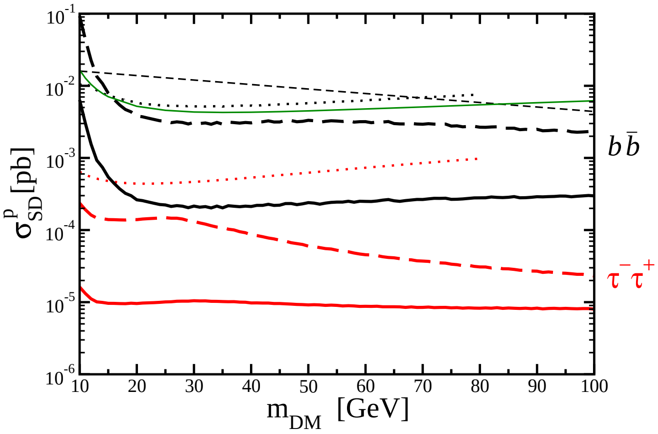

Figure 2: ***Limits on the WIMP-proton spin-dependent cross section at 90% CL.*** *Black (upper) lines refer to annihilations into $b\bar{b}$ and red (lower) lines to annihilations into $\tau^-\tau^+$. Thick lines represent the limits expected with DeepCore after 10 years, including (dashed lines) and not including (solid lines) systematic errors. The limit for the $b\bar{b}$ channel using stopping and through-going muons in Super-Kamiokande [14] is shown with the thin black dashed line. Limits using fully-contained muon-like and upward stopping muons in Super-Kamiokande [15] are shown with the dotted lines. The limits from the combination of the revised Stage 1 and Stage 2 of the SIMPLE experiment are depicted by the green solid line [13].*

The results of the present letter rely on the capability of DeepCore to reconstruct the (muon) energy spectrum: distinguishing between hard and soft channels allows to get information on the initial annihilation channels, mass and WIMP-proton cross section. If only the total number of events is measured, a strong degeneracy is present among these parameters [7]. In particular, here we focus on the determination of the DM mass, marginalizing over the rest of the parameters, i.e., the annihilation branching ratios and the WIMP-proton cross section. We leave for future work the study of the sensitivity of DeepCore to these properties [21].

The main results of this letter are depicted in Fig. 1, where the relative error in the determination of the DM mass ($m^{\rm exp}$ is mass determined by the experiment) is presented for DM annihilations into $\tau^-\tau^+$ (top panel) and into $b\bar{b}$ (bottom panel). For each annihilation mode we consider two values for the WIMP-proton spin-dependent cross section: $\sigma^{\rm p}_{\rm SD} = 10^{-3}$ pb (in blue), 10^{-4} pb (in orange) for the $\tau^-\tau^+$ channel and $\sigma^{\rm p}_{\rm SD} = 10^{-2}$ pb (in blue), 4×10^{-3} pb (in orange) for the $b\bar{b}$ channel. As can be seen from Fig. 2, for the $\tau^-\tau^+$ channel and $m_{\rm DM} < 80$ GeV, $\sigma^{\rm p}_{\rm SD} = 10^{-3}$ pb is excluded at 90% CL from Super-Kamiokande data [15]. On the other hand, for the $b\bar{b}$ channel, $\sigma^{\rm p}_{\rm SD} = 10^{-2}$ pb is also excluded at 90% CL for some masses in the range depicted from Super-Kamiokande data [14, 15]. However, note that these analyses do not include systematic uncertainties. In Fig. 1 we show the results including (light colors) and not including (dark colors) systematic errors as discussed above. We can see that if the WIMP-proton spin-dependent cross section has a value very close to the current Super-Kamiokande limit, the DM mass could be determined (including systematic errors) within a $\sim 50\%$ uncertainty for $\rm m_{DM} < 100$ GeV if DM annihilates dominantly into $b\bar{b}$ or within a few percent for 30 GeV $\lesssim \rm m_{DM} < 100$ GeV if the dominant DM annihilation channel is $\tau^-\tau^+$.

Systematic uncertainties may have a strong impact on the achievable precision and their detailed evaluation will play an important role. In addition to the channels considered here, other channels could be present, as annihilations directly into neutrino pairs, that would give rise to a line in the neutrino energy spectrum, leading to the hardest, and easiest to detect, muon spectra in IceCube/DeepCore and a better determination of the DM mass. Conversely, softer channels would very likely lead to worse results. Moreover, as the IceCube/DeepCore neutrino telescope is sensitive to much higher DM masses, in this case new channels are possible, as annihilations into gauge bosons or into top quarks. We leave some of these questions for future work [21].

Conclusions.— In this letter we have studied the capabilities of the DeepCore Array to determine the DM mass in the case of light WIMPs, i.e., 10 GeV < $m_{\rm DM}$ < 100 GeV, by measuring the spectrum of muon-like events. We have marginalized over two possible annihilation channels that we have taken as benchmarks for hard ($\tau^-\tau^+$) and soft ($b\bar{b}$) channels and over the WIMP-proton cross section. We have shown that in the case of a cross section close to the current Super-Kamiokande limits, an excellent measurement of the mass could be possible (see Fig. 1). Therefore the DeepCore Array provides a new avenue for the determination of the DM mass which is complementary to other searches [2–6] and should be consistently combined. This would allow to reduce different sources of uncertainty and to constrain several DM properties, critical steps to determine the DM identity.

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