Searching for dark matter with neutrino telescopes

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Abstract. One of the most interesting mysteries of astrophysics is the puzzle of dark matter. Although numerous techniques have been explored and developed to detect this elusive substance, its nature remains unknown. One such method uses large high-energy neutrino telescopes to look for the annihilation products of dark matter annihilations. In this paper, we briefly review this technique. We describe the calculations used to find the rate of capture of WIMPs in the Sun or Earth and the spectrum of neutrinos produced in the resulting dark matter annihilations. We will discuss these calculations within the context of supersymmetry and models with universal extra dimensions, the lightest supersymmetric particle and lightest Kaluza–Klein particle providing the WIMP candidate in these cases, respectively. We will also discuss the status of some of the experiments relevant to these searches: AMANDA, IceCube and ANTARES.

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1. Introduction

There exists an enormous body of evidence in favour of cold dark matter. This evidence includes observations of galactic clusters and large-scale structure [1], supernovae [2] and the cosmic microwave background (CMB) anisotropies [3, 4]. Recently, WMAP has provided the most detailed information on the CMB to date, quoting a total matter density of $\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$ [4]. Furthermore, data from WMAP and other earlier experiments indicate a considerably smaller quantity of baryonic matter [4, 5]. At the 2σ confidence level, the density of non-baryonic and cold dark matter is now known to be $\Omega_{CDM} h^2 = 0.113^{+0.016}_{-0.018}$ [4].

Many methods have been proposed to search for evidence of particle dark matter. In addition to accelerator searches, direct and indirect dark matter detection experiments have been performed. Direct dark matter searches attempt to measure the recoil of dark matter particles scattering elastically off the detector material [6]. Indirect dark matter searches have been proposed [7] to observe the products of dark matter annihilation including $\gamma$-rays [8, 9], positrons [10], anti-protons [11] and neutrinos [12].

Each of these methods has its advantages and disadvantages. Direct detection is most suited for WIMPs with relatively large elastic scattering cross-sections with nucleons. Indirect detection using $\gamma$-rays is often studied in the context of observing annihilations in the galactic centre region, which depends significantly on the dark matter profile used. Alternatively, dark matter substructure could be studied with this method. However, this would still depend on poorly known dark matter distributions [9]. Measurements of the local anti-proton or positron cosmic-ray spectrum depend critically on the location of, and amount of, dark matter substructure within tens of kiloparsecs and a few kiloparsecs, respectively. Also, positrons and anti-protons do not point towards their sources making an unambiguous separation from backgrounds very difficult.

WIMPs which scatter elastically in the Sun or Earth may become gravitationally bound in these gravitational wells. Over the age of the solar system, they may accumulate in substantial numbers in these objects, greatly enhancing their annihilation rate. Although $\gamma$-rays, positrons and anti-protons produced in these annihilations do not escape the Sun or Earth, neutrinos often can. Also, unlike other indirect dark matter searches this method does not depend strongly on our galaxy’s dark matter halo profile or on the distribution of dark matter substructure. In this paper, we review this method of indirect dark matter detection, and discuss the prospects for such observations in existing and planned experiments.

2. Particle dark matter candidates

Numerous particles have been discussed in the literature as dark matter candidates. It would be impossible and undesirable for us to attempt to review all of them here. Instead, we will focus on two examples which arise in popular particle physics scenarios: supersymmetry and models with universal extra dimensions.

2.1. Supersymmetry

In models with supersymmetry, each fermion has a bosonic partner (and vice versa), which exactly cancels all quadratic divergences to the Higgs mass, thus naturally solving one of the major problems associated with the standard model. Furthermore, the lightest supersymmetric
particle (LSP) is stable in most viable models due to the conservation of R-parity [13]. In many supersymmetric models, the LSP is the lightest neutralino, a mixture of the superpartners of the photon, Z and neutral higgs bosons, and is electrically neutral, colourless and a viable dark matter candidate [14].

If such a particle were in equilibrium with photons in the early universe, as the temperature decreased, a freeze-out would occur, leaving a thermal relic density. The temperature at which this occurs and the density which remains depends on the annihilation cross-section and mass of the lightest neutralino. It is natural for supersymmetry to provide a dark matter candidate with a present abundance similar to those favoured by the WMAP experiment.

The details of any SUSY model are subject to the way supersymmetry is broken (i.e. how masses are given to the superpartners). Most often, the LSP is predominantly gaugino, although it is possible to have a substantial higgsino fraction in some cases.

2.2. Universal extra dimensions

Models with extra dimensions appearing at or near the TeV scale have become very popular in recent years. One class of these models are those in which all of the fields of the standard model propagate in ‘universal’ extra dimensions [15, 16]. In these models, Kaluza–Klein (KK) excitations appear as particles with masses of the scale of the extra dimension. Due to conservation of momentum in the higher dimensions, a symmetry called KK parity can arise which can, in some cases, make the lightest KK particle (LKP) stable [17]. KK-parity functions in a way which is analogous to R-parity in supersymmetric models, making it possible for the LKP to be a viable dark matter candidate [18].

The identity of the LKP depends on the mass spectrum of the first KK level. The LKP is, most naturally, the first KK excitation of the B°. The KK spectrum to one-loop level is given in [19]. Using this spectrum, the relic density of the LKP can be calculated as a function of its mass. It has been found that the appropriate density is predicted when the mass is moderately heavy, between 600 and 1200 GeV [18], somewhat heavier than the range favoured for supersymmetry. This range of the LKP mass depends on the details of the co-annihilations of LKPs with heavier KK particles.

Another difference between dark matter particles in universal extra dimensions and supersymmetry is that unlike for a neutralino LSP, the bosonic nature of the LKP means there is no chirality suppression of the annihilation signal in fermions. The annihilation rate of the LKP is therefore roughly proportional to the hypercharge of the final state, leading to a large rate in leptons, including neutrinos. The annihilation and co-annihilation cross-sections are determined by standard model couplings and the mass spectrum of the first KK level.

3. Capture and annihilation in the Sun

To provide an observable flux of neutrinos, dark matter particles must be gathered in high concentrations. Deep gravitational wells such as the Sun, Earth or galactic centre are examples of regions where such concentrations may be present. In the following calculation, we will focus on the Sun, as its prospects are the most promising.

The rate at which WIMPs are captured in the Sun depends on the nature of the interaction the WIMP undergoes with nucleons in the Sun. For spin-dependent interactions, the capture rate...
is given by [20]
\[
C_{\text{SD}}^\odot \simeq 3.35 \times 10^{20} \text{s}^{-1}\left( \frac{\rho_{\text{local}}}{0.3 \text{ GeV cm}^{-3}} \right) \left( \frac{270 \text{ km s}^{-1}}{\bar{v}_{\text{local}}} \right)^3 \left( \frac{\sigma_{\text{H,SD}}}{10^{-6} \text{ pb}} \right) \left( \frac{100 \text{ GeV}}{m_{\text{DM}}} \right)^2
\],
\hspace{1cm} (1)

where \( \rho_{\text{local}} \) is the local dark matter density, \( \sigma_{\text{H,SD}} \) the spin-dependent WIMP-on-proton (hydrogen) elastic scattering cross-section, \( \bar{v}_{\text{local}} \) the local rms velocity of halo dark matter particles and \( m_{\text{DM}} \) is our dark matter candidate. The analogous formula for the capture rate from spin-independent (scalar) scattering is [20]
\[
C_{\text{SI}}^\odot \simeq 1.24 \times 10^{20} \text{s}^{-1}\left( \frac{\rho_{\text{local}}}{0.3 \text{ GeV cm}^{-3}} \right) \left( \frac{270 \text{ km s}^{-1}}{\bar{v}_{\text{local}}} \right)^3 \left( \frac{2.6\sigma_{\text{H,SI}} + 0.175\sigma_{\text{He,SI}}}{10^{-6} \text{ pb}} \right) \left( \frac{100 \text{ GeV}}{m_{\text{DM}}} \right)^2.
\] \hspace{1cm} (2)

Here, \( \sigma_{\text{H,SI}} \) is the spin-independent WIMP-on-proton elastic scattering cross-section and \( \sigma_{\text{He,SI}} \) the spin-independent WIMP-on-helium elastic scattering cross-section. Typically, \( \sigma_{\text{He,SI}} \simeq 16.0\sigma_{\text{H,SI}} \). Factors of 2.6 and 0.175 include information on the solar abundances of elements, dynamical factors and form factor suppression.

Although these two rates appear to be comparable in magnitude, the spin-dependent and spin-independent cross-sections can differ radically. For example, with KK dark matter, the spin-dependent cross-section is typically 3–4 orders of magnitude larger than the spin-independent cross-section [18], and solar accretion by spin-dependent scattering dominates.

If the capture rates and annihilation cross-sections are sufficiently high, the Sun will reach equilibrium between these processes. For \( N \) (number of) WIMPs in the Sun, the rate of change of this number is given by
\[
\dot{N} = C^\odot - A^\odot N^2,
\] \hspace{1cm} (3)

where \( C^\odot \) is the capture rate and \( A^\odot \) the annihilation cross-section times the relative WIMP velocity per volume. \( C^\odot \) is as defined in (1), whereas \( A^\odot \) is
\[
A^\odot = \frac{\langle \sigma v \rangle}{V_{\text{eff}}},
\] \hspace{1cm} (4)

with \( V_{\text{eff}} \) being the effective volume of the core of the Sun determined roughly by matching the core temperature with the gravitational potential energy of a single WIMP at the core radius. This was found in [21] to be
\[
V_{\text{eff}} = 5.7 \times 10^{27} \text{ cm}^3 \left( \frac{100 \text{ GeV}}{m_{\text{DM}}} \right)^{3/2}.
\] \hspace{1cm} (5)

The present WIMP annihilation rate is
\[
\Gamma = \frac{1}{2} A^\odot N^2 = \frac{1}{2} C^\odot \tanh^2 \left( \sqrt{C^\odot A^\odot} t_\odot \right),
\] \hspace{1cm} (6)
where $t_\odot \simeq 4.5$ billion years is the age of the solar system. The annihilation rate is maximized when it reaches equilibrium with the capture rate. This occurs when

$$\sqrt{C^\odot A^\odot t_\odot} \gg 1.$$  

(7)

For the majority of particle physics models which are most often considered (e.g., most supersymmetry or KK models), the WIMP capture and annihilation rates reach or nearly reach equilibrium in the Sun. This is often not the case for the Earth. This is true for two reasons. First, the Earth is less massive than the Sun and, therefore, provides fewer targets for WIMP scattering and a less deep gravitational well for capture. Secondly, the Earth accretes WIMPs only by scalar (spin-independent) interactions. For these reasons, it is unlikely that the Earth will provide any observable neutrino signals from WIMP annihilations in any planned experiments.

If very high densities of dark matter are present in the galactic centre, such as expected for very cuspy halo profiles [22] or density spikes [23], sizable neutrino fluxes could be produced. For most particle dark matter candidates, however, very large fluxes of $\gamma$-rays would accompany such neutrinos and it would be unlikely that neutrinos would be observed in the absence of a $\gamma$-ray signal. However neutrino experiments could help confirm that a $\gamma$-ray signal was the result of dark matter annihilations rather than a more traditional astrophysical source.

4. Neutrinos and their detection

The rate of neutrinos produced in WIMP annihilations is highly model-dependent as the annihilation fractions to various products can vary largely from model to model. We will attempt to be as general in our discussion as possible while still considering some specific cases.

In supersymmetry, there are no tree level diagrams for direct neutralino annihilation to neutrinos. However, many indirect channels exist. These include neutrinos from heavy quarks, gauge bosons, tau leptons and higgs bosons. These processes result in a broad spectrum of neutrinos, but with typical energies of 1/2 to 1/3 of the neutralino mass. For experimental energy thresholds of 10–100 GeV, lighter WIMPs can be very difficult or impossible to detect for this reason.

For neutralinos lighter than the $W^\pm$ mass (80.4 GeV), annihilation to $b\bar{b}$ typically dominates, with a small admixture of $\tau^+\tau^-$ as well. In these cases, neutrinos with less than about 30 GeV energy are produced and detection is difficult. For heavier neutralinos, annihilation into gauge bosons, top quarks and higgs bosons are important in addition to $b\bar{b}$ and $\tau^+\tau^-$. In particular, gauge bosons can undergo two-body decay ($Z \rightarrow \nu\nu$ or $W^\pm \rightarrow l^\pm\nu$) producing neutrinos with an energy of about half of the WIMP mass. Neutralinos with substantial higgsino components often annihilate mostly into gauge bosons.

For KK dark matter, the picture is somewhat different. The LKP annihilates directly to a pair of neutrinos about 3–4% of the time [18, 24]. Although this fraction is small, the neutrinos are of higher energy and are, therefore, easier to detect. The more frequent annihilation channels for KK dark matter are charged leptons (60–70%) and up-type quarks (20–30%). Of these, the $\tau^+\tau^-$ mode contributes the most to the neutrino flux. Unlike in supersymmetry, a large fraction of LKPs annihilate into long-lived particles, such as up-quarks, electrons and muons, which lose their energy in the Sun long before decaying. Bottom and charm quarks lose some energy before decaying, but not significantly.
Neutrinos which are produced lose energy as they travel through the Sun [25]–[27]. The probability of a neutrino escaping the Sun without interaction is given by [27]

$$P = e^{-E_\nu/E_k},$$  

(8)

where $E_k$ is $\simeq 130$ GeV for $\nu_\mu$, $\simeq 160$ GeV for $\nu_e$, $\simeq 200$ GeV for $\bar{\nu}_\mu$ and $\simeq 230$ GeV for $\bar{\nu}_e$. Thus we see that neutrinos above a couple of hundred GeV are especially depleted, although those which escape are also more easily detected. For a useful parametrization of solar effects, see [25]. Note that neutrino oscillations can also play an important role in calculating the flux of muon neutrinos in a detector [27].

A small fraction of the muon neutrinos which reach the detector are converted into muons through charged current interactions [28]. These muons then propagate through the Cerenkov medium of the detector, where they are detected by photomultiplier tubes distributed through the effective volume. For a review of high-energy neutrino astronomy, see [29].

As a muon propagates, it loses energy at the rate

$$\frac{dE}{dX} = -\alpha - \beta E,$$  

(9)

where $\alpha = 2.0$ MeV cm$^2$ g$^{-1}$ and $\beta = 4.2 \times 10^{-6}$ cm$^2$ g$^{-1}$. The distance a muon travels before dropping below the threshold energy, called the muon range, is then given by [30]

$$R_\mu \simeq \frac{1}{\rho \beta} \ln \left[ \frac{\alpha + \beta E_\mu}{\alpha + \beta E_{\mu{\text{thr}}}} \right],$$  

(10)

where $\rho$ is the density of the detector medium, $\alpha \simeq 2.0$ MeV cm$^2$ g$^{-1}$ and $\beta \simeq 4.2 \times 10^{-6}$ cm$^2$ g$^{-1}$. $E_{\mu{\text{thr}}}$ is the energy threshold of the detector, typically 10–100 GeV for deep ice or water detectors. The effective volume in which a muon producing interaction can occur and be observed is simply the muon range times the effective area of the detector.

Currently, the AMANDA experiment is taking data at the South Pole [31]. With an effective area of 50,000 m$^2$ and a muon energy threshold of about 30 GeV, AMANDA is currently the largest volume high-energy neutrino telescope. Due to its ‘soda can’ geometry, however, it is not very sensitive in the direction of the Sun (the horizon), and thus only places useful limits from the centre of the Earth. As we said before, the rate of dark matter annihilations in the Earth is much smaller than in the Sun, making detections unlikely.

ANTARES [32], now under construction in the Mediterranean, will not have this problem. With a lower energy threshold (10 GeV) and larger effective area (100,000 m$^2$), ANTARES will be significantly more sensitive to dark matter annihilations compared with AMANDA. Unlike neutrino telescopes at the south pole, ANTARES will also be sensitive to neutrinos coming from the galactic centre.

IceCube [33], under construction at the South Pole, will have a full square kilometre of effective area, but with a somewhat higher energy threshold (50–100 GeV). Unlike its predecessor, AMANDA, IceCube will be sensitive to neutrinos in the direction of the Sun.

The background for this class of experiments consists of atmospheric neutrinos [34] and neutrinos generated in cosmic ray interactions in the Sun’s corona [35]. In the direction of the Sun (up to the angular resolution of a neutrino telescope), tens of events $> 100$ GeV and of the order of 1 event per year $> 1$ TeV km$^{-2}$ are expected from the atmospheric neutrino flux. Fortunately,
Figure 1. The number of events from neutralino annihilation in the Sun per year in a detector with effective area equal to 1 km\(^2\) and a 50 GeV muon threshold [36]. The lightly shaded region represents the general minimal supersymmetric standard model (MSSM), the darker region corresponds to mSUGRA models, a subset of the MSSM. For each point shown, the relic density is below the maximum value allowed by the WMAP data ($\Omega_\chi h^2 \leq 0.129$). The sensitivity projected for IceCube is shown as a broken line [37].

for a very large-volume detector with sufficient statistics, this background is expected to be significantly reduced and possibly eliminated. Furthermore, this rate could be estimated based on the rate from atmospheric neutrinos, a level of about a few events per year. The final background is then further reduced by selecting on judiciously chosen angular and/or energy bins. Neutrinos generated by cosmic ray interactions in the Sun’s corona, however, cannot be reduced in this way. This irreducible background is predicted to be less than a few events per year per square kilometre > 100 GeV.

5. Prospects

The current limits on dark matter annihilation from AMANDA and other similar experiments are not very strong. Experiments with lower energy thresholds (ANTARES), larger effective areas (IceCube) and which can observe in the direction of the Sun (ANTARES and IceCube) will greatly enhance this sensitivity in coming years.

The sensitivity of a square-kilometre neutrino detector with a moderate muon energy threshold (50 GeV) to supersymmetric dark matter is shown in figure 1. From this figure,
it is clear that high-energy neutrinos will be an observable signature in only a small fraction of possible supersymmetry models, although such experiments are still certainly an important probe.

For KK dark matter, the prospects for detection via high-energy neutrinos are substantially better. This is largely due to which annihilation modes dominate. The spectrum of muons in a detector on Earth due to LKP annihilations in the Sun is shown in figure 2 for various annihilation channels and for two choices of LKP mass. Unlike for supersymmetry, annihilation to neutrinos and taus dominate the neutrino spectrum. In supersymmetry, b quarks and gauge bosons dominate, producing fewer observable neutrinos.

In figure 3, the event rates in a square-kilometre detector are shown (using a threshold of 50 GeV). Each of the three lines corresponds to a different value of the next-to-lightest KK particle’s mass. The expected size of the one-loop radiative corrections predicts $0.1 \lesssim r_{q_1} \lesssim 0.2$, where $r_{q_1}$ is the mass splitting of the LKP and the next-to-LKP over the LKP mass. For this range, a kilometre-scale neutrino telescope would be sensitive to a LKP with mass up to about 1 TeV. The relic density of the LKP varies from low to high values from left to right in the figure. The range of mass of the LKP that gives the appropriate relic density was estimated from [18] and is shown in the figure by the solid sections of the lines. Combining the expected size of the one-loop radiative corrections with a relic density appropriate for dark matter, we see that IceCube should see a few to tens of events per year.

For detectors with smaller effective areas one simply has to scale the curves down by a factor $A/(1 \text{ km}^2)$ to obtain the event rate. In particular, for the first-generation neutrino telescopes.
Figure 3. The number of events per year from KK dark matter annihilation in the Sun in a detector with an effective area equal to $1 \text{ km}^2$ and a muon energy threshold of $50 \text{ GeV}$ [24]. Contours are shown, from bottom to top, for $r_{q_k} = 0.1$, 0.2 and 0.3, where $r_{q_k}$ is the mass splitting of the LKP and the next-to-LKP over the LKP mass. The expected size of the one-loop radiative corrections predict $0.1 \lesssim r_{q_k} \lesssim 0.2$; therefore, the $r_{q_k} = 0.3$ contour is shown merely for comparison. The relic density of the LKPs lies within the range $\Omega_{\text{B}} h^2 = 0.16 \pm 0.04$ for the solid sections of each line. The relic density is smaller (larger) for smaller (larger) LKP masses.

including AMANDA, ANTARES and NESTOR, with effective areas of order $0.1 \text{ km}^2$, the event rate could be as high as a few events per year for a LKP mass at the lower end of the solid line region.

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