Indirect Detection of Dark Matter in km-size Neutrino Telescopes

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Abstract

Neutrino telescopes of kilometer size are currently being planned. They will be two or three orders of magnitude larger than presently operating detectors, but they will have a much higher muon energy threshold. We discuss the trade-off between area and energy threshold for indirect detection of neutralino dark matter captured in the Sun and in the Earth and annihilating into high energy neutrinos. We also study the effect of a higher threshold on the complementarity of different searches for supersymmetric dark matter.

1 Introduction

Neutrino astrophysics will soon enter a new experimental era. With the demonstration by the AMANDA collaboration (see e.g. Halzen, 1999) of the possibility to instrument and successfully deploy kilometer-long strings with optical modules in the ice cap at the South Pole station, the road to a km^3 detector lies open. At the same time, endeavours are underway (NESTOR, ANTARES, BAIKAL) to prove the possibility of also deploying a large neutrino detector in a deep lake or ocean.

This new generation of neutrino telescopes will have a larger effective area than earlier detectors, but the energy threshold will be higher. A typical energy threshold for these larger detectors is of the order of 25–100 GeV, and we will here consider thresholds of 1, 10, 25, 50 and 100 GeV. As we will show, for the dark matter detection capability, a low threshold is an important design criterion to be kept in mind when planning new neutrino telescopes.

As a WIMP candidate we will use the neutralino, that naturally arises in supersymmetric extensions of the standard model (see e.g. Jungman et al., 1997).

2 Set of supersymmetric models

We work in the minimal supersymmetric standard model with seven phenomenological parameters and have generated about 10^5 models by scanning this parameter space (for details, see Bergström et al., 1998). For each generated model, we check if it is excluded by recent accelerator constraints of which the most important ones are the LEP bounds (Carr, 1998) on the lightest chargino mass (about 85–91 GeV), and the lightest Higgs boson mass $m_{H_2^0}$ (which range from 72.2–88.0 GeV) and the constraints from $b \to s\gamma$ (Ammar et al., 1993 and Alam et al. 1995).

For each model allowed by current accelerator constraint we calculate the relic density of neutralinos $\Omega_\chi h^2$ where the relic density calculation is done as described in Edsjö and Gondolo (1997), i.e. including so called coannihilations. We will only be interested in models where neutralinos can be a major part of the dark matter in the Universe, so we restrict ourselves to relic densities in the range $0.025 < \Omega_\chi h^2 < 0.5$.

3 Muon fluxes from neutralino annihilations

The prediction of muon rates is quite involved: we compute neutralino capture rates in the Sun and the Earth (using the convenient approximations in Jungman et al. (1997)), branching ratios for different annihilation channels, fragmentation functions in basic annihilation processes, interactions of the annihilation products with the surrounding medium (where appropriate), propagation through the solar or terrestrial medium, charged current cross sections and muon propagation in the rock, ice or water surrounding the detector.

We simulate the hadronization and/or decay of the annihilation products, the neutrino interactions on the way out of the Sun and the neutrino interactions close to or in the detector with PYTHIA 6.115 (Sjöstrand,

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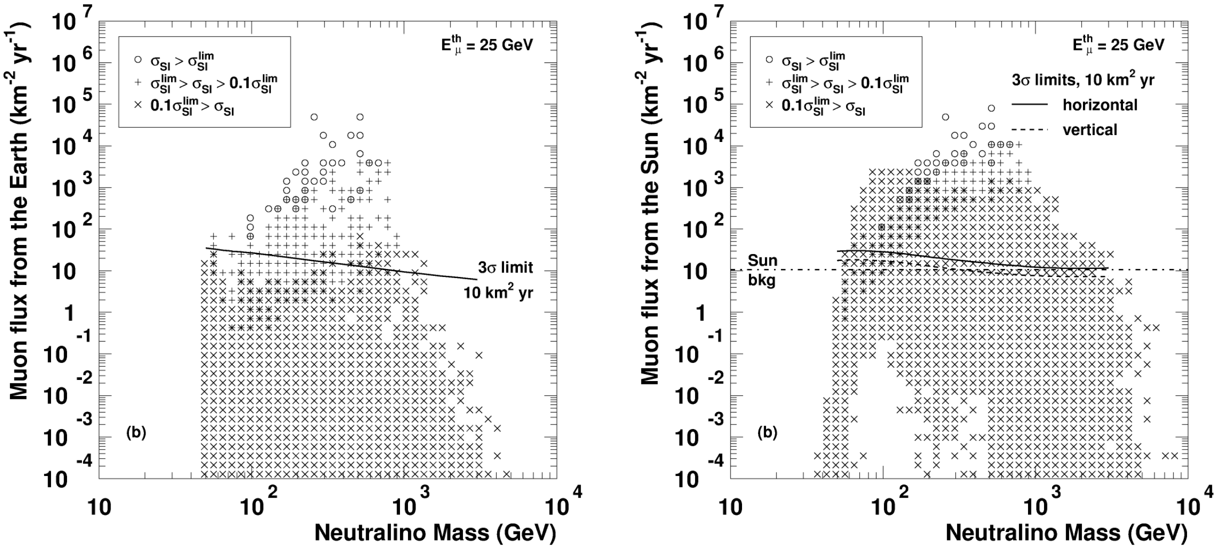

Figure 1: The neutrino-induced muon flux from neutralino annihilations in a) the Earth and b) the Sun. The expected limits that can be obtained with an exposure of 10 km^2 yr are also shown. The models that can be probed by present direct dark matter searches (Bernabei et al., 1996), those that can be probed with a factor of 10 increased sensitivity and those that cannot be probed with direct searches are shown with different symbols.

1994). We treat the interactions of the heavy hadrons in the centre of the Sun and the Earth in an approximate manner as given in Edsjö (1997).

3.1 Backgrounds and signal extraction. The most severe background is the atmospheric background produced by cosmic rays hitting the Earth's atmosphere (see e.g. Honda et al., 1995). For the Sun, there is also a background from cosmic ray interactions in the Sun (Seckel et al., 1991 and Ingelman & Thunman, 1996) which is small but irreducible (at least as long as energy is not measured).

To investigate the possible limits that can be obtained, we will follow the analysis of Bergström et al. (1997) and parameterize the neutrino-induced muon flux by

$$\frac{d^2\phi_s}{dEd\theta}(E,\theta) = \phi_s^0 \left[a f_{\rm hard}(m_\chi, E, \theta) + (1-a) f_{\rm soft}(m_\chi, E, \theta) \right], \qquad (1)$$

where a is a model-dependent parameter describing the 'hardness' of the neutrino-induced muon spectrum, $f_{\rm hard}$ and $f_{\rm soft}$ are generic hard and soft muon spectra and ϕ_s^0 is the normalization of the flux. A typical hard spectrum is given by the annihilation channel W^+W^- and a typical soft spectrum is given by the annihilation channel $b\bar{b}$. We now assume that the annihilation spectrum is hard and that ϕ_0 is the only unknown. If we relax these assumptions the limits will be up to a factor of 2–3 higher.

For very high exposures ($\mathcal{E} > 10$ km^2 yr) towards the Sun, the above limits will be too optimistic due to the background from cosmic ray interactions in the Sun's corona. This background will have about the same angular distribution as the neutralino signal from the Sun, but quite different energy distribution. With a neutrino telescope without energy resolution, this background will put a lower limit on how small fluxes we can probe from the Sun. The background fluxes are about 20, 13, 11, 8.6 and 6.6 muons km^{-2} yr^{-1} for muon energy thresholds of 1, 10, 25, 50 and 100 GeV respectively.

3.2 Dependence on energy threshold. As an example of a probably realistic threshold of a km-size neutrino telescope, we choose 25 GeV and in Fig. 1 (a) and (b) we show the muon fluxes versus the neutralino mass. We also show the best limits obtainable with an exposure of 10 km^2 yr, and for the Sun, the background from cosmic ray interactions in the Sun's corona. Note that for high masses, there is no need to go above

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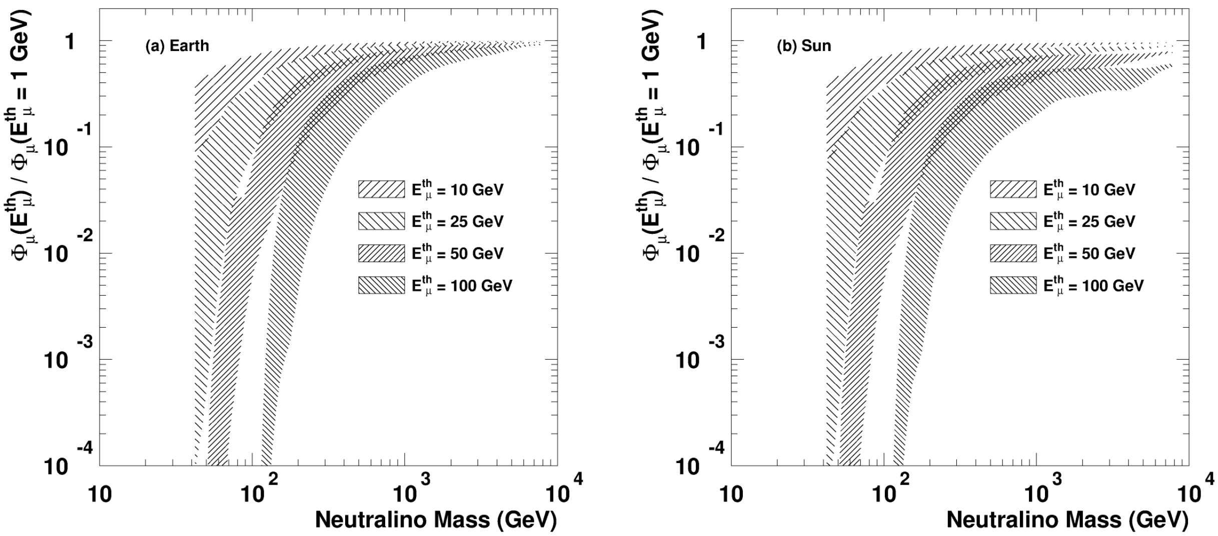

Figure 2: The ratio of the muon fluxes for different thresholds to those with a threshold of 1 GeV.

an exposure of about 10 km^2 yr towards the Sun (unless the detector has good energy resolution) due to the irreducible background from the Sun's corona. For lower masses, the corresponding exposure would be 10^2 km^2 yr.

In Fig. 2 we show the ratio of the muon flux with different thresholds E_μ^{th} to those with a threshold of 1 GeV. The width of the bands reflects the different degrees of softness of the neutrino spectra for a given neutralino mass. The softer the neutrino spectrum, the more we lose by increasing the threshold.

We see that if the neutralino mass is above the threshold energy by a fair amount, not too many events are lost by increasing the energy threshold. This is because the detection rate is determined by the second moment of the neutrino energy (one power of energy because of the rise of the neutrino cross section, and one power because of the increasing muon path length). So the most energetic muons dominate the rate. A higher threshold may even be more advantageous than a low one, because it also reduces the background from atmospheric neutrinos.

For the Sun, we see that there is always a loss even at the highest masses. This is due to the absorption of neutrinos in the interior of the Sun, which softens the neutrino spectra. When the threshold exceeds 100 GeV, at least half of the signal from the Sun is lost whatever the neutralino mass is.

As an example, if the neutralino mass were 200 GeV, increasing the threshold from 1 to 100 GeV could decrease the signal by a factor of between 10 and 1000. On the other hand, if the threshold can be kept at 25 GeV or below, we see that on the average only a factor of 2–3 is lost for a 200 GeV neutralino, from either the Sun or the Earth. It is thus highly desirable to keep the threshold as low as possible to keep the signal high.

The above discussion is true for muons traversing a thin detector. However, for $\mathcal{O}(1 \text{ km}^3)$ neutrino telescopes, we would expect the event rates for contained events (i.e. tracks starting or stopping inside the detector) to be high also for masses below a few hundred GeV. This can be expressed by an effective area that increases for low-mass neutralinos. If this would be taken into account, the limits shown in Fig. 1 would go down by up to a factor of 10 at low masses. We also note that for fully contained events (i.e. events both starting and stopping in the detector) it would be possible to get an energy estimate from the track length and in this case about another factor of 2 can be gained in sensitivity.

4 Comparison with other signals

The uncertainty in the capture rates governing the muon flux enter in a similar way in the calculation of the rates of direct detection. In Fig. 1 we show with different symbols models that can be probed with current

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direct detection experiments and what could be obtained with a factor of 10 increase in sensitivity. In the Earth, the correlation is fairly strong, whereas it is weaker in the Sun. The reason is that the capture rate in the Sun depends on the spin-dependent scattering cross section as well as the spin-independent one.

We can also look for neutralinos by searching for their annihilation products from annihilation in the halo. The most interesting sources are gamma lines, continuum gammas, antiprotons and positrons. The correlation with these signals is fairly weak and they thus represent fairly complementary methods of searching for neutralino dark matter. We do get higher uncertainties from the halo profile and propagation (for charged particles) though.

One of the earliest precursors of the MSSM may be the discovery of the Higgs boson at accelerators, where the lightest neutral Higgs scalar H_2^0 in supersymmetric models hardly can be heavier than 130 GeV after loop corrections (Carena et al., 1995) have been included. We find models with high muon rates (regardless of the threshold) all the way up to the heaviest H_2^0 allowed in the MSSM. An MSSM Higgs boson of mass near the 130 GeV limit will not be detectable by LEP II, and may require several years of LHC running for its discovery.

5 Conclusions

We have seen that the higher threshold of the new generation of neutrino telescopes reduces the rates for low-mass neutralinos whereas the suppression is less severe for high-mass models. For muons from the Earth, the suppression means that neutrino telescopes will have some difficulties to compete with direct detection methods. For the Sun the situation is different as the spin-dependent cross section has a larger spread, and there do not yet exist direct detectors of large sensitivity. From the point of view of neutralino search, the optimum design of a neutrino telescope would have a low muon energy threshold and a good sensitivity to search for a signal from the direction of the Sun.

Various methods of detecting supersymmetric dark matter probe complementary regions of parameter space, and are therefore all worth pursuing experimentally. The dark matter problem remains one of the outstanding problems of basic science. Maybe the first clues to its solution will come from the large new neutrino telescopes presently being planned.

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