Neutrino Oscillation Effects in Indirect Detection of Dark Matter

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Abstract. If neutrino oscillation plays a role in explaining the atmospheric neutrino deficit, then the same phenomenon would necessarily affect also the dark matter indirect-detection signal which consists in a muon-neutrino flux produced by neutralino annihilation in the Earth core. In this paper we investigate to which extent the upgoing-muon signal originated by neutralinos captured inside the Earth would be affected by the presence of $\nu_\mu \rightarrow \nu_\tau$ oscillation.

1 Introduction

Among the different techniques which have been proposed to search for dark matter particles [1], detection of a neutrino flux by means of neutrino telescopes represents certainly an interesting tool. Although direct detection [2,3,4] at present appears to be somewhat more sensitive to neutralino dark matter [5,6,7], nevertheless all the different possibilities are worth being explored. In this paper we discuss the flux of upgoing muons which are a consequence of $\nu_\mu$’s produced inside the Earth, with special emphasis on the role which is played in this kind of searches by the possible presence of neutrino oscillation.

2 Upgoing $\mu$’s from neutralino annihilation in the Earth

Neutralinos can be gravitationally captured inside astrophysical bodies [8], like the Earth and the Sun. Their subsequent annihilation can produce a flux of neutrinos, which then travel toward a detector located underground below the Earth surface. The differential flux, for each neutrino flavour $i$, is defined as

$$\Phi^{0}_{\nu_i}(E_\nu) \equiv \frac{dN_{\nu_i}}{dE_\nu} = \frac{\Gamma_A}{4\pi d^2} \sum_{F,f} B_{\chi f}^{(F)} \frac{dN_{\nu_i}}{dE_i},$$

where $\Gamma_A$ denotes the neutralino annihilation rate, $d$ is the distance between the detector and the source (which can be the center of the Earth or the Sun), $F$ is an index which lists all the possible final states which can be produced by neutralino pair-annihilation, $B_{\chi f}^{(F)}$ denotes, for each final state $F$, the branching ratios into heavy quarks, $\tau$ leptons and gluons. The differential spectra of neutrinos and antineutrinos generated by the $\tau$ and by hadronization of quarks and gluons...
and the subsequent semileptonic decays of the produced hadrons are denoted by $dN_{\ell^-}/dE_{\nu}$. For more details, see for instance Refs. [2,3,9,10]. Here we only recall that the annihilation rate depends, through its relation with the capture rate of neutralinos in the Earth, on some astrophysical parameters, the most relevant of which is the local density $\rho_l$.

The best way of identifying the presence of these fluxes relies on the possibility to detect upward going muons inside a neutrino telescope. These upgoing muons would be produced by the $\nu_\mu$ component of the neutrino fluxes of Eq.(1). The charged-current interaction of the $\nu_\mu$’s with the rock below and close to the detector would produce a flux of muons. A double-differential muon flux is defined as

$$\frac{d^2N_\mu}{dE_\mu dE_{\nu}} = \sum_j N_A \int_0^\infty dX \int_{E_{\nu}}^{E_{\mu}} dE'_\mu \Phi_j(E_\nu) \frac{d\sigma_j(E_\nu, E'_\mu)}{dE'_\mu},$$

(2)

where $j = \nu_\mu, \bar{\nu}_\mu$, $N_A$ is the Avogadro’s number, $g(E_\mu, E'_\mu; X)$ is the survival probability that a muon of initial energy $E'_\mu$ will have a final energy $E_\mu$ after propagating along a distance $X$ inside the rock and $d\sigma_j(E_\nu, E'_\mu)/dE'_\mu$ is the charged-current cross section for the production of a muon of energy $E'_\mu$ from a neutrino (antineutrino) of energy $E_\nu$.

A useful quantity for our discussion is the muon response function

$$\frac{dN_\mu}{dE_{\nu}} = \int_{E_{\nu}}^{E_{\nu}^{\text{th}}} dE_\mu \frac{d^2N_\mu}{dE_\mu dE_{\nu}},$$

(3)

where $E_{\nu}^{\text{th}}$ is threshold energy for detection of up–going muons. For Super Kamiokande and MACRO, $E_{\nu}^{\text{th}} \approx 1.5$ GeV [12]. The muon response function identifies the neutrino energy range that is most responsible for the up–going muon signal. Fig. 1 shows a few examples of it, plotted as functions of the variable $x = E_\nu/m_\chi$, where $m_\chi$ denotes the neutralino mass. Fig. 1 shows an approximate scaling of $dN_\mu/dE_{\nu}$ with $m_\chi$. The maximum of the muon response occurs for neutrino energies of about $E_\nu \approx (0.4 – 0.6) m_\chi$, with a half width which extends from $E_\nu \approx 0.1 m_\chi$ to $E_\nu \approx 0.8 m_\chi$.

The quantity which is actually measured is the total flux of up–going muons, which is defined as

$$\Phi_\mu = \int_{E_{\nu}^{\text{th}}}^{m_\chi} dE_\nu \frac{dN_\mu}{dE_{\nu}}.$$ 

(4)

$\Phi_\mu$ can be calculated once a specific supersymmetric model is adopted. In the case of a model where all the supersymmetric parameters are defined and set at the electroweak scale (which we call here MSSM), the result for $\Phi_\mu$ is shown in Fig. 2. We have varied the MSSM parameters in the ranges: $20 \text{ GeV} \leq M_2 \leq 1000 \text{ GeV}$, $20 \text{ GeV} \leq |\mu| \leq 1000 \text{ GeV}$, $90 \text{ GeV} \leq m_A \leq 1000 \text{ GeV}$, $100 \text{ GeV} \leq m_0 \leq 1000 \text{ GeV}$, $-3 \leq A \leq +3$, $1 \leq \tan \beta \leq 50$. Up-to-date bounds and limits coming from accelerators and from BR($b \to s\gamma$) have been imposed. For a definition of supersymmetric models and their parameters, as well as the implementation of
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the experimental limits on susy searches, see Ref. [5]. For calculations of $\Phi_\mu$ in supergravity inspired (SUGRA) models, see Ref. [11].

Fig. 2 also shows the present most stringent upper limit obtained by the MACRO Collaboration [13]. Super Kamiokande recently also reported a similar upper bound [14].

3 Neutrino oscillation effect on the up–going muon signal

The atmospheric neutrino deficit strongly points toward the indication that the $\nu_\mu$ may oscillate. The oscillation channel which best describes the anomaly is $\nu_\mu \rightarrow \nu_\tau$ vacuum oscillation [15,16]. If this is the case, also the $\nu_\mu$ produced by neutralino annihilations would undergo an oscillation process. The range of energies involved in both atmospheric and neutralino–produced neutrinos is approximately the same, while the baseline of oscillation of the two neutrino components is different Atmospheric neutrinos which induce upgoing muons cover a range of pathlengths which ranges from twice the Earth’s radius, for vertical muons, to much shorter distances in the case of horizontal muons. On the contrary, neutrinos produced by neutralino annihilation in the central part of the Earth travel a distance of the order of the Earth’s radius to reach the detector. On the basis of the features of the $\nu_\mu$ oscillation which are required to fit the experimental data on atmospheric neutrinos [15,16], we expect that also the neutrino flux from dark matter annihilation would be affected [17].

For $\nu_\mu \rightarrow \nu_\tau$ oscillation, the $\nu_\mu$ flux is reduced because of oscillation, but we have to take into account that neutralino annihilation can also produce $\nu_\tau$ which in turn can oscillate into $\nu_\mu$ and contribute to the up–going muon flux. The muon neutrino flux can therefore be expressed as (we are considering only two-flavour oscillation)

$$
\Phi_{\nu_\mu}(E_\nu) = \Phi^0_{\nu_\mu} P^{\text{vac}}(\nu_\mu \rightarrow \nu_\mu) + \Phi^0_{\nu_\tau}[1 - P^{\text{vac}}(\nu_\mu \rightarrow \nu_\tau)] ,
$$

where the vacuum survival probability is [18]

$$
P^{\text{vac}}(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta) \sin^2 \left( \frac{1.27 \Delta m^2 (\text{eV}^2) R (\text{Km})}{E_\nu (\text{GeV})} \right) ,
$$

where $\Delta m^2$ is the mass square difference of the two neutrino mass eigenstates, $\theta$ is the mixing angle in vacuum and $R$ is the Earth’s radius. Fig. 3 shows the survival probability for two different values of the neutrino oscillation parameters which are inside their allowed ranges [15,16]. Smaller (larger) values of $\Delta m^2$ have the effect of shifting the curves to the left (right). Comparing Fig. 1 with Fig. 3, we notice that the reduction of the up–going muon flux is stronger when there is matching between the the energy $E_\nu^1 \simeq 5.2 \cdot 10^3 \Delta m^2 (\text{eV}^2)$ of the first (from the right) minimum of the survival probability and the energy $E_\nu \simeq 0.5 m_\chi$ which is responsible for most of the muon response in the detector. This implies that a maximum reduction of the signal could occur for neutralino masses of
the order of $m_\chi (\text{GeV}) \simeq 10^4 \Delta m^2 (\text{eV}^2)$. The $\nu_\tau \rightarrow \nu_\mu$ oscillation makes the reduction of the muon flux less severe, but it is not able to completely balance the reduction effect because the original $\nu_\tau$ flux at the source is smaller than the $\nu_\mu$ flux. Therefore, the overall effect of the neutrino oscillation is to reduce the up-going muon signal. The upgoing muon flux for a neutralino in the MSSM, when neutrino oscillation is included, is given in Fig. 4. This, when compared with Fig. 2, shows the effect induced by the presence of oscillation. The ratio of the up-going muon signals in the presence and in the absence of oscillation is plotted in Fig. 5. We notice that the strongest effect occurs for light neutralinos, since in this case the muon flux is mostly produced from neutrinos whose energy is in the range of maximal suppression for the oscillation phenomenon. The effect is between 0.5 and 0.8 for $m_\chi \lesssim 100 \text{ GeV}$. On the contrary, the fluxes for larger masses are less affected, and the reduction is less than about 20% for $m_\chi \gtrsim 200 \text{ GeV}$. Figs. 2, 4 and 5 update the corresponding figures of Ref. [19] by the inclusion of the new limits from accelerator on Higgs and Supersymmetry searches.

4 Conclusions

In this paper we have discussed to which extent neutrino oscillation can affect the up-going muon signal from neutralino annihilation in the Earth. While the experimental upper limit is, at present, practically not affected by neutrino oscillation [3], the theoretical predictions are reduced in the presence of oscillation. By adopting the neutrino oscillation parameters deduced from the fits on the atmospheric neutrino data [15,16], the effect is always larger for lighter neutralinos. For $\nu_\mu \rightarrow \nu_\tau$ the reduction is between 0.5 and 0.8 for $m_\chi \lesssim 100 \text{ GeV}$ and less than about 20% for $m_\chi \gtrsim 200 \text{ GeV}$.

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Fig. 1. Muon response function $dN_{\mu}/d\log x$ vs. the parent-neutrino fractional energy $x = E_\nu/m_\chi$ for neutralino annihilation in the Earth. Different curves refer to different neutralino masses: $m_\chi = 50$ GeV (solid), $m_\chi = 80$ GeV (dotted), $m_\chi = 120$ GeV (shot–dashed), $m_\chi = 200$ GeV (long–dash), $m_\chi = 500$ GeV (dot–dashed).
Fig. 2. Flux of up-going muons $\Phi_{\mu}^{\text{Earth}}$ from neutralino annihilation in the Earth, plotted as a function of $m_\chi$. The solid line denotes the present upper limit from MACRO \cite{13}. Crosses denote supersymmetric configurations for which the neutralino relic abundance $\Omega_\chi h^2$ is larger than, or equal to, the value 0.05 (but not in excess of its cosmological upper bound of 0.7 \cite{5}). Dots stand for $\Omega_\chi h^2 < 0.05$. The $\nu_\mu$’s are assumed not to oscillate.
Fig. 3. $\nu_\mu$ survival probability in the case of $\nu_\mu \to \nu_\tau$ oscillation. The solid line refers to $\sin^2(2\theta) = 1$, the dashed line is for $\sin^2(2\theta) = 0.8$. In both cases, $\Delta m^2 = 5 \cdot 10^{-3} \text{ eV}^2$. 
Fig. 4. Flux of up-going muons \( \Phi_{\mu}^{\text{Earth}} \) from neutralino annihilation in the Earth, plotted as a function of \( m_\chi \). The solid line denotes the present upper limit from MACRO [13]. Crosses denote supersymmetric configurations for which the neutralino relic abundance \( \Omega_\chi h^2 \) is larger than, or equal to, the value 0.05 (but not in excess of its cosmological upper bound of 0.7 [5]). Dots stand for \( \Omega_\chi h^2 < 0.05 \). The \( \nu_\mu \)'s are assumed to oscillate into \( \nu_\tau \)'s, with oscillation parameters fixed at the best-fit values of Ref. [15]: \( \sin^2(2\theta) = 1 \) and \( \Delta m^2 = 3 \times 10^{-3} \text{eV}^2 \).
Fig. 5. Scatter plot of the ratio \( \frac{\Phi^{\text{Earth}}_{\mu, \text{oscill}}}{\Phi^{\text{Earth}}_{\mu}} \) vs. the neutralino mass \( m_\chi \). \( \Phi^{\text{Earth}}_{\mu, \text{oscill}} \) is the up–going muon flux in the case of \( \nu_\mu \rightarrow \nu_\tau \) oscillation (shown in Fig.4), while \( \Phi^{\text{Earth}}_{\mu} \) is the corresponding flux in the case of no oscillation and (plotted in Fig.2). For the oscillation case, the neutrino parameters have been set at the best-fit values of Ref. [15]: \( \sin^2(2\theta) = 1 \) and \( \Delta m^2 = 3 \cdot 10^{-3} \text{ eV}^{-2} \).