Downward-going tau neutrinos and Dark Matter

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Abstract. We discuss the possibility of detecting the downward–going tau neutrino flux from Dark Matter annihilation inside the Sun. In our analysis we focused on the hadronic showers produced by charged–current tau neutrino interactions followed by hadronic tau decay. We include the various sources of tau neutrino backgrounds as well as experimental sources of background due to misidentification of electron and muon events. We find that the downward–going tau neutrino signal has potentially very good prospects for Mton–scale Cherenkov detectors, if the level of misidentification of non–tau events is at the level of percent. In this case, within few years of exposure, a 5σ significance discovery is potentially reachable for Dark Matter masses in the range from 20 to 300 GeV.

1. Introduction
Indirect Dark Matter (DM) searches look for the products of DM self–annihilation (or decay) occurring in the galactic halo, in the extragalactic environment or in those celestial bodies, like the Sun and the Earth, where they can be gravitationally trapped and accumulated. As a consequence of DM annihilations, a flux of high–energy neutrinos can emerge. In general, the flux is composed by all three neutrino flavours, but the typical signal which is looked at refers to the $\nu_\mu$ component and consists of a flux of up–going muons in a neutrino detector. In this case, the major source of background is given by atmospheric muon neutrinos.

In this talk, which is based on Ref. [1], we propose, instead, a novel signature: the possibility of looking at the $\nu_\tau$ component of the DM signal coming from the Sun. This is almost background–free in the downward–going direction, since the $\nu_\tau$ amount in atmospheric neutrinos is negligible and atmospheric $\nu_\mu$ do not sizably oscillate in the down–going baseline.

In Sect. 2 we discuss the neutrino fluxes coming from DM annihilation and the background fluxes: the atmospheric, solar corona and galactic neutrinos. The class of signals relevant for water Cherenkov detectors, i.e. the hadronic contained events, is then presented. We discuss both the signal events from tau decay as well as the background contributions due to misidentified electron and muon events. In Sect. 3 we show the level of sensitivity that can be achieved on the DM spin–independent cross section on protons $\sigma_p$. The capabilities of Mton–scale water Cherenkov detectors are also presented. Conclusions are given in Sect. 4.

2. Background and signal events
The neutrino flux at the detector, coming from DM annihilation inside the Sun, is calculated as described in Ref. [2], considering neutrino oscillations and neutrino neutral current ($N\nu$) and
charged current ($CC$) interactions. We consider two DM annihilation channels: into neutrinos with flavor–blind branching ratios and into tau leptons.

The $\nu_\tau$ coming from oscillation of atmospheric $\nu_\mu$ [3] represents one source of background to the $\nu_\tau$ DM signal. There are, however, three other forms of background: the intrinsic $\nu_\tau$ contribution to the atmospheric flux [4], the neutrino flux produced in the solar corona [5] and the fluxes of tau neutrinos from the galactic plane [6].

For (GeV–TeV) energies, $CC \nu_\tau$ interactions in water Cherenkov detectors will lead to multiple Cherenkov rings and the possibility of identifying these events is currently based only on statistical methods. Considering the hadronic decays of tau leptons, the misidentified events for the Super–Kamiokande detector is of the order of several percent [7, 8]. The experimental backgrounds that we consider are $N\bar{C}$ events from $\nu_\tau$ and $\nu_\mu$ atmospheric neutrinos and $CC$ events from $\nu_e$.

The expression for the contained hadronic tau events is given by [9]

$$N_{\tau}^{CC} \mid_{S,B} = M_{det} N_y \times \int_{E_{vis}^{min}}^{E_{vis}^{max}} dE_{vis} \int d\Omega \eta(\theta) \left( \frac{d^2T_{\tau}^{CC}}{d\Omega dE_{vis}} \right)_{S,B} ,$$

with $M_{det} N_y$ being the detector exposure, $\eta(\theta)$ the on–source duty factor and

$$\left( \frac{d^2T_{\tau}^{CC}}{d\Omega dE_{vis}} \right)_{S,B} = \int dE_\nu \int dE_\tau \frac{d^2\phi_{\nu_\tau}}{d\Omega dE_\nu} \left( \frac{\Sigma_{\tau}^{CC}(E_\tau, E_\nu)}{dE_{vis}} \right)_{S,B} + (\nu \to \bar{\nu}),$$

where $S$ and $B$ denote signal and background and $d^2\phi_{\nu_\tau}/d\Omega dE_\nu$ the $\nu_\tau$ flux. The function $\Sigma_{\tau}^{CC}$ quantifies the number of interactions, while $d\Gamma_h/dE_{vis}$ the decay rate of tau into hadrons [1].

In the left panel of Fig. 1, we show the number of downward–going signal events from hadronic tau decay as a function of the DM mass $m_\chi$, for $M_{det} N_y = 1$ Mton$\times$year and for $\sigma_p = 10^{-41}$ cm$^2$. The number of signal events can reach the level of 50 or more, depending on $m_\chi$. For the annihilation channels under study, this signal is most sensitive to DM masses in the range from 30 GeV up to 200–300 GeV. In the same figure, we also show the negligible number of $CC$ events expected from the $\nu_\tau$ background. The $N\bar{C}$ events from atmospheric $\nu_\mu$ and $\nu_e$ as well as the $CC$ events from $\nu_e$ are also shown. These classes of events pose a problem if they are not controlled at a level better than a few percent.

3. Detectability and statistical significance

To quantify the discovery reach of present and future water Cherenkov detectors, we use the statistical significance $\varsigma$, defined as the signal–to–noise ratio:

$$\varsigma \equiv \frac{S}{\sqrt{S+B}} .$$

In the ideal case, in which no misidentification is present and the detector efficiency for tau leptons $\epsilon_{\tau}$ is 100%, the background contribution is given by $B_{ideal} = N_{\tau}^{CC} \mid_B$. In a more realistic case, in which the misidentification and the detection efficiency for taus are considered, we have:

$$B_{realistic} = \epsilon_{\tau} N_{\tau}^{CC} \mid_B + \epsilon_{\mu}^{min} N_{\mu}^{CC} \mid_B + \epsilon_{e}^{min} \left( N_{e}^{NC} \mid_B + N_{e}^{CC} \mid_B \right).$$

We show in the right panel of Fig. 1 the contours for $\varsigma = 1.64$ (which corresponds to a 90% C.L. upper bound) in the plane $\sigma_p$ vs. $m_\chi$, for an exposure $M_{det} N_y = 1$ Mton$\times$year. The dotted lines represent the limits without considering misidentification, while the solid lines correspond to $\epsilon_{\tau} = 40\%$ and $\epsilon_{e}^{min} = 4\%$. We show the allowed regions obtained from the DAMA [10],
Figure 1. Left: Number of downward–going $\nu_\tau$ hadronic events as a function of $m_\chi$, for $\sigma_p = 10^{-41}$ cm$^2$ and $M_{\text{det}}N_y = 1$ Mton$\times$year. The horizontal lines represent the NC events expected from the atmospheric $\nu_e$ and $\nu_\mu$, and the CC events from atmospheric $\nu_e$ and background $\nu_\tau$. Right: Limits at 90% C.L. ($\varsigma = 1.64$) on $\sigma_p$ as a function of $m_\chi$, for $M_{\text{det}}N_y = 1$ Mton$\times$year. The dotted lines represent the limits without considering misidentification, while the solid lines correspond to $\epsilon_\tau = 40\%$ and $\epsilon_{\text{mis}} = 4\%$. We show also the allowed regions from DAMA (orange solid line: without channeling, orange dashed line: with channeling), CoGeNT (dot–dashed red curve) and CRESST (cyan regions), and the limits from XENON 100 (green dashed line) and CDMS (gray dashed line) experiments.

Figure 2. Iso–contours of statistical significance ($\varsigma = 2$, 3 and 5 $\sigma$) for the detection of downward–going $\nu_\tau$ hadronic events as a function of detector exposure (in kton $\times$ year) and DM mass $m_\chi$, for $\sigma_p = 10^{-41}$ cm$^2$ (left panel: annihilation into neutrinos, right panel: annihilation into tau leptons). The two horizontal lines denote the exposures that can be reached by a 0.5 Mton detector, like HK, in 1 and 10 years. The detection efficiency is fixed to $\epsilon_\tau = 70\%$, while the misidentification to $\epsilon_{\text{mis}} = 1\%$. 
CoGeNT [11] and CRESST [12] positive results, see Ref. [13] for more details. The constraints from the XENON [14] and CDMS [15] experiments are also shown [16].

In Fig. 2 we present the iso–contours of statistical significance, $\zeta = 2, 3$ and 5 $\sigma$, for the detection of downward–going $\nu_\tau$ hadronic events as a function of $m_\chi$ and of the detector exposure. We consider $e_{\tau} = 70\%$, $e_{\mu}^{\text{mis}} = e_{\mu}^{\text{mis}} = 1\%$ and $\sigma_p = 10^{-41}$ cm$^2$. The horizontal lines denote the exposures that can be reached by a 0.5 Mton detector, like Hyper-Kamiokande (HK) [17], in 1 and 10 years. A few years of exposure would suffice to cover almost the whole DM mass range for our benchmark value of $\sigma_p$. The recent analyses of direct detection annual modulation effects observed by DAMA [10] and CoGeNT [11] (and the excess reported by CRESST [12]) point toward a DM candidate with $m_\chi \simeq 10$ GeV and $\sigma_p$ of the order of $10^{-42}$ cm$^2 - 10^{-40}$ cm$^2$. For this type of particle, we would expect, for direct annihilation into neutrinos, between 9 and 900 hadronic events and a detection close to 5 $\sigma$ with a 10 years exposure on HK (5 Mton×yr).

4. Conclusion

We propose a new channel for DM searches at neutrino telescopes: the downward–going hadronic tau events originated by the $\nu_\tau$ signal produced in DM annihilations in the Sun. This specific signal potentially represents a very good opportunity for DM detection, since the background of atmospheric downward–going $\nu_\tau$ is extremely reduced with respect to the upward–going $\nu_\mu$, case commonly considered.

At water Cherenkov detectors, unfortunately, the hadronic tau events cannot be easily distinguished from $\mathcal{NC}$ events, mostly coming from atmospheric $\nu_e$ and $\nu_\mu$, and by $\mathcal{CC}$ $e$–like events. We found that the misidentification of non–tau events needs to be kept at the level of percent to have potentially good prospects for detecting DM through the downward–going tau neutrinos signal at future Mton–size Cherenkov detectors.

We showed that several tens of events per year (depending on the DM mass and annihilation channel) are potentially collectible in a Mton–scale detector. In the case of $e_{\tau} = 70\%$ and of $e_{\mu}^{\text{mis}} = e_{\mu}^{\text{mis}} = 1\%$, a 5 $\sigma$ significance discovery is potentially reachable for DM masses in the range from 20 to 300 GeV with a few years of exposure, and for $\sigma_p = 10^{-41}$ cm$^2$.

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