PROCEEDINGS OF SCIENCE

Conversion of Neutrino Fluxes from Dark Matter Self-annihilations in the Sun to WIMP-nucleon Scattering Cross Sections

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We investigate conversion factors of expected neutrino fluxes generated by self-annihilating dark matter in the Sun to the WIMP-nucleon scattering cross section. We provide a procedure for the treatment of uncertainties related to the conversion.

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1. Introduction

There is compelling observational evidence for the existence of dark matter; however, its nature remains unknown. A wide-range of particle candidates suggest numerous possible signals, from the byproducts of self-annihilations or decays, or from scattering of nuclei. Weakly Interacting Massive Particles (WIMPs) are leading particle dark matter candidates, predicted to have masses ranging from a few 10 GeV to several TeV [1].

Neutrinos are ideal messengers in the search for WIMPs. They can be used to probe its self-annihilation cross section as well as the WIMP-nucleon scattering cross section. For the latter neutrino telescopes are able to set very stringent limits for the spin-dependent case [2, 3]. Such sensitivities are achieved by looking for neutrino signals from self-annihilating dark matter gravitationally captured by the Sun. The capture mechanism of dark matter is initiated by the same event that direct detection experiments try to observe: a nuclear recoil in which a WIMP transfers some of its kinetic energy to a nucleon. For the common case of equilibrium between capture rate, Γ_{C}, and annihilation rate, Γ_{A}, neutrino fluxes, ϕ_{ν}^{f}, from the Sun are directly comparable to rates at direct detection experiments. The problem of converting a muon neutrino generated muon flux, ϕ_{μ}^{f}, to direct detection rates has been studied extensively [4, 5]. The DarkSUSY [6] package allows one to obtain conversion factors for given halo and SUSY parameters.

In the past searches were centered around muon neutrino induced muon rates; however, searches relying on other neutrino flavors are also feasible. Once the detector diameter is of comparable size to the muon range of for the neutrino energies of interest, vertex contained event rates (from ν_e, ν_μ, ν_τ interactions) are large compared to those induced by muons from ν_μ interactions outside the detector volume. The usage of vertex contained events for analyses has been well established and is documented for Super Kamiokande [7]. The comparison of fluxes of all neutrino flavors to the spin-dependent WIMP-nucleon scattering cross section, σ^{SD}, is the focus of these proceedings. Neutrino fluxes are in particular sensitive to σ^{SD} as the Sun is predominantly a Hydrogen target. The work is based on a study using DarkSUSY version 5.0.4. We further provide a description how to incorporate and treat uncertainties. In particular we address uncertainties due to the dark matter distribution, which are common to all searches.

2. Neutrino flux conversion

Previous searches have focused on the muon neutrino induced muon flux at neutrino telescopes for obvious reasons: (1) The good pointing resolution of high-energy muons allows us to define a small search window around the Sun. It can further be used in rejecting the large background caused by down-going atmospheric muons. (2) The long range of high-energy muons (~ 1 km in water at 200 GeV), allows for the detection of ν_μ interacting outside the instrumented detector volume. Advances in detection methods with operating neutrino detectors and prospects for future detectors allow for the expansion of Solar WIMP searches to other neutrino flavors. Not only could these provide additional information on the WIMP properties, in case of a detected signal, but searches relying on vertex contained events can generally achieve also a better energy resolution.

The use of conversion factors for neutrino fluxes compared to muon fluxes holds some distinct advantages. Inherently, they do not depend on muon propagation effects and allow us to treat all neutrino flavors in the same way. The muon flux is also highly dependent on the opening angle given around the Sun, motivated by the kinematic angle between the muon neutrino and the muon ($\Delta\phi \simeq 1^\circ \times \sqrt{1\text{TeV}/E_\nu}$) and some detector dependent uncertainty in the muon directional reconstruction. As annihilation occur almost entirely near the center of the Sun, the resulting neutrino flux shows a negligible dependence on the opening angle compared to achievable angular resolutions on neutrino directional reconstruction. Further, if the muon range is on the same order as the size of the detector, then there is no longer a significant increase in effective area due its range. We also note that neutrinos fluxes with energies above 1 TeV are severely attenuated and neutrinos above 100 GeV encounter significant absorption effects in the Sun. Hence, neutrino searches are limited to an energy range below a few hundred GeV.

We assume that the annihilation rate in the Sun is regulated by the capture rate. A treatment for deviations from this equilibrium condition will be discussed in the next section. In this study we set the local halo density to 0.3 GeV/cm^3, assume $v_\odot = 220$ km/s as the velocity of the Sun relative to the halo, and 270 km/s as the WIMP velocity dispersion. The velocity distribution is assumed to be Maxwellian.

Under the assumption of a neutrino energy detection threshold of $E_\nu^{\text{thr}} = 1$ GeV, we compute conversion factors for all three neutrino flavors and various annihilation channels. Figure 1 shows the obtained conversion factors. $\sigma^{\text{SD}}/\phi_\nu^f$ is identical for ν_μ and ν_τ and the difference relative to ν_e is driven by differences in the injection spectrum and oscillations. For the neutrino oscillation, we used the parameters described in Ref. [8] as $\theta_{12} = 33.2^\circ$, $\theta_{13} = 0^\circ$, $\theta_{23} = 45^\circ$, $\delta = 0$, $\Delta m^2_{21} = 8.1 \times 10^{-5} eV^2$ and $|\Delta m^2_{31}| = 2.2 \times 10^{-3} eV^2$. The choice of these oscillation parameters is not very sensitive to our calculation though. Motivated by stringent constrains from direct detection experiments [9], we assume that the spin-independent WIMP-nucleon cross section is negligible, $\sigma^{\text{SI}} = 0$, and capture in the Sun is dominated by σ^{SD}. Alternatively, one can use a neutrino flux limit from the Sun to probe σ^{SI}. For this condition in practice results are roughly two orders of magnitude smaller compared to σ^{SD} (see e.g. ref. [10]).

3. Treatment of uncertainties

In this section we discuss uncertainties related to the flux conversion. For our uncertainty treatment, we divide them in three different categories that are uncorrelated to each other: (1) annihilation rate at equilibrium, (2) neutrino propagation, (3) neutrino detection. This grouping simplifies the error treatment as they can be considered separately.

We first discuss the uncertainty on the annihilation rate at equilibrium, which is driven by the uncertainty on the capture rate. The impact of evaporation relevant for light WIMPs (~ 4 GeV) [11] is not discussed here. The capture rate depends on the properties of the dark matter distribution at the solar circle, r_{SC}. The simplest dependence is on the dark matter density uncertainty given by $\Delta\Gamma_{\text{A}}/\Gamma_{\text{A}} = \Delta\rho_{\text{DM}}/\rho_{\text{DM}}$. The dependence on the velocity distributions is non-trivial. Figure 2 shows the change in capture rate for different parameters for a Maxwellian velocity distribution, which is often assumed but recently disfavored. We vary halo parameters by about 10% as this at is on the same as the common understanding of these parameters.

Deviations from a smooth halo profile at the solar circle through substructure would introduce a time dependence on the strength of the neutrino flux from the Sun. N-body simulations

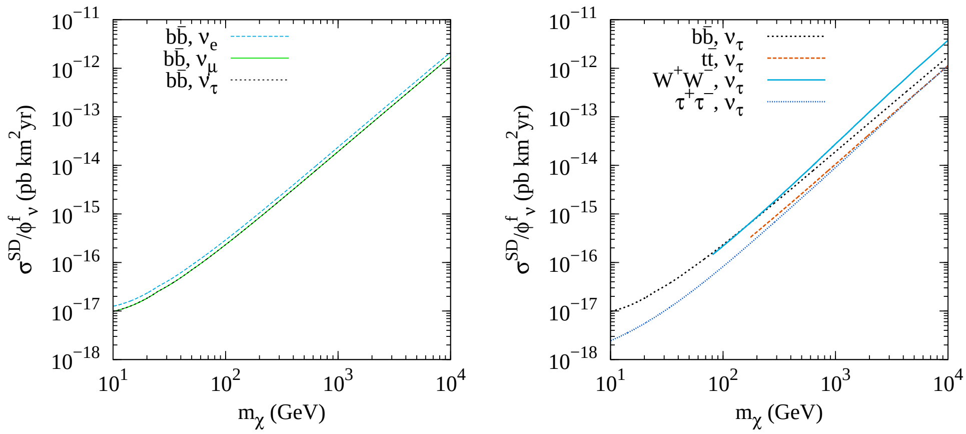

Figure 1: Flux conversion of the spin-dependent WIMP-nucleon scattering cross section to the neutrino flux at Earth from dark matter annihilations in the Sun under the condition that the annihilation rate is regulated by the capture rate (equilibrium condition). We assume that the spin-independent WIMP-nucleon scattering cross section is small as indicated by tide constraints from direct detection experiments [9]. Left: Flux conversion for different neutrino flavors and a given annihilation channel ($b\bar{b}$). Right: Flux conversion for various annihilation channels for one election neutrino fluxes.

disfavor any significant sub structure at r_{SC} [12]. Small variations in the local dark matter density and velocity distribution can generally be covered by the overall uncertainty on the average dark matter density and velocity distribution. We do not consider extreme scenarios with significant substructure, as for such cases it would be impossible to derive a conversion factor without detailed knowledge of solar substructure history.

Other uncertainties on the capture rate, which we did not include yet, are related to the solar composition and the impact of planets. The latter one would reduce the neutrino flux in a cross section dependent way for WIMP masses above a few TeV [13].

While the equilibration time scale is typically short compared to the age of the Sun, in some scenarios the Sun is not in equilibrium. In this case the annihilation rate would be reduced and only be a fraction of the maximal flux achieved at equilibrium. Based on a MSSM-7 [14] parameter scan we determine the ratio of the expected flux compared to the maximal flux achieved at equilibrium. While simple approximations exists that determine the equilibrium time scale we found them to vary wildly from the results obtained with the DarkSUSY scan. The average flux fraction is shown in figure 3. It can be seen that for the near future accessible parameter space the equilibrium condition is in general satisfied.

Neutrino propagation needs to include matter effects in the Sun, which include oscillations as well as absorption and tau regeneration. Further, vacuum oscillations need to be considered on the way from the Sun to the Earth. These effects have been discussed elsewhere [15, 16]. The described oscillations effects are fully treated in DarkSUSY and their associated uncertainties are generally small compared to the uncertainties associated to the annihilation rate.

The third independent component in the uncertainties associated with the flux conversion is related to the neutrino detection and detector site itself. It makes sense to separate out this component as it strongly depends on the properties of the experiment. The associated uncertainties are

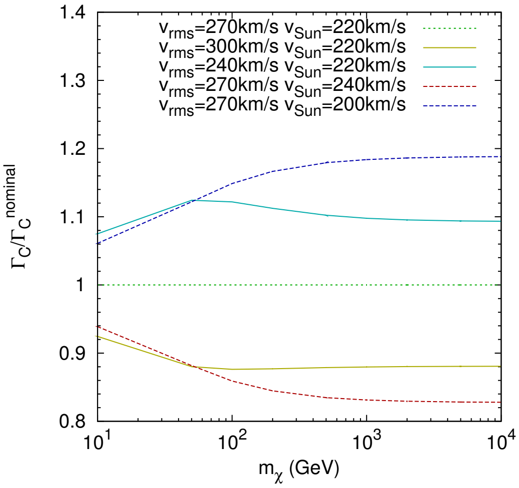

Figure 2: Dependence of the capture rate on halo parameters as function of the WIMP mass. The velocity of the Sun relative to the halo and the WIMP velocity dispersion get varied by $\pm 10\%$. The velocity distribution is assumed to be Maxwellian.

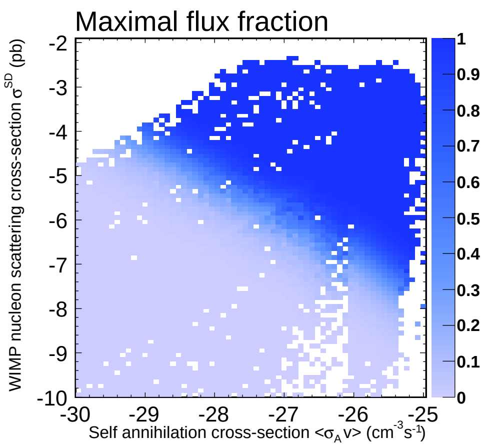

Figure 3: Based on a MSSM-7 parameter scan we determine the ratio of the expected flux compared to that achieved at equilibrium, as function of the self-annihilation cross section and WIMP-nucleon scattering cross section.

a combination of theoretical uncertainties such as the neutrino cross section, as well as the Earth composition at the interaction point as well as long the neutrino path through the Earth (relevant for oscillation effects in matter and muon propagation for the case of muon neutrinos). Detector related effects for neutrino detectors such as ANTARES, IceCube, and Super Kamiokande, include uncertainties due to light propagation and sensor efficiencies. Based on past analyses, such uncertainties typically sum up to about 20-25%.

4. Conclusions

We have studied the comparison of neutrino fluxes from the Sun with the spin dependent WIMP-nucleon cross section using DarkSUSY. We provide a procedure for the treatment of systematic uncertainties associated with the flux conversion and investigated the impact of these uncertainties with a particular focus on the dark matter distributions. Uncertainties were evaluated with respect to the neutrino flux ϕ_ν^f, which are equivalent to the uncertainty to the conversion factor. However, the uncertainties do not necessarily apply if neutrino fluxes are compared to direct detection rates, as some of them are correlated. For a more detailed discussion please see Ref. [17].

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