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χaroν: a tool for neutrino flux generation from WIMPs

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Indirect searches for signatures of corpuscular dark matter have been performed using all cosmic messengers: gamma rays, cosmic rays, and neutrinos. The search for dark matter with neutrinos is important since they are the only courier that can reach detectors from dark matter processes in dense environments, such as the core of the Sun or Earth, or the edge of the observable Universe. One thing essential to experiments is the prediction of the neutrino signature in the detector. I will introduce χaroν, a software that bridges the dark sector and Standard Model by predicting neutrino fluxes from different celestial dark matter agglomerations in diverse scenarios. This package includes an updated computation of neutrino production and propagation to the detector.

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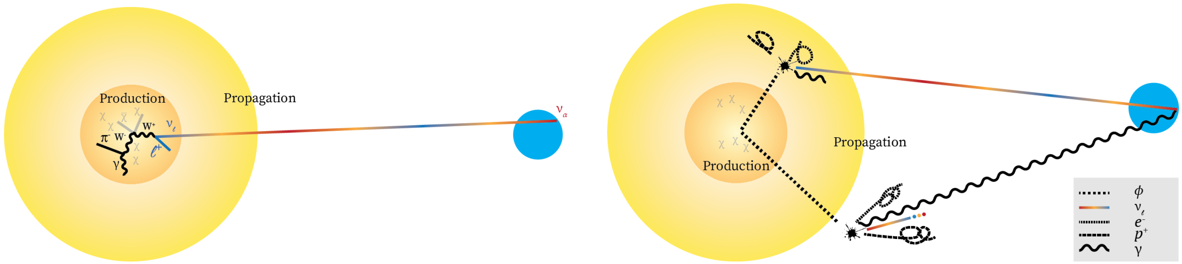

Figure 1: *Left Panel:* WIMP annihilation to SM particles. These primary annihilation products, which in this illustration is W^+W^-, decay to other SM particles of which only neutrinos are able to leave the production region while other messenger attenuate in side the object. *Right Panel:* The secluded DM scenario. WIMPs are secluded from the SM and predominantly communicates with it via a long-lived annihilation or decay mediator, ϕ. The dotted line represents this mediator. If the average decay length is less than the radius of the source, then as in the standard case, only neutrinos will escape. On the other hand, if this length is longer than the radius of the source, then neutrinos, gamma rays, e^+e^- and $p\bar{p}$ can escape the source as well.

1. Introduction

The existence of dark matter (DM) has been strongly established by astrophysical and cosmological observations and DM is expected to comprise about 85% of the Universe's present matter content in the ΛCDM model. However, the nature and identity of DM are still not currently known. A number of DM candidates have been put forward. Among them, WIMPs are a class of elementary particles beyond the Standard Model which were thermally produced in the early Universe, which can naturally explain the present abundance of DM. WIMPs are neutral and assumed to be stable over cosmological scales. They interact gravitationally, and are assumed to possess additional interactions at or below the weak scale.

Intensive efforts have been made to detect signatures of DM through various strategies in complementary to each other. Production of DM on colliders is being studied and nuclear recoils of WIMP-nucleon interactions in liquid noble gases such as argon and xenon, or organic compounds are being measured, which is refered to as direct detection. Another method is to search for DM indirectly by detecting the annihilation or decay standard model (SM) products from the Universe. No matter what channels these processes have, the final fluxes are composed of stable particles, electrons, neutrinos, photons and protons. As DM particles interact gravitationally, they can accumulate where there is a large gravitational field. For example, they assemble in Galactic Halos or can be captured and condense in heavy celestial bodies, such as the Sun and Earth. In the latter case, neutrinos are the only annihilation/decay products which can escape their source since other messengers are likely to be fully absorbed inside.

In order to detect neutrino signals from DM, it is important to simulate the neutrino flux expected at detectors. The currently widely used fluxes in neutrino experiments such as ANTARES, IceCube, Super-Kamiokande (See e.g. [1–4]) are from DarkSUSY [5], PPPC [6, 7], `WimpSim` [8, 9], and direct PYTHIA [10] generation. There similarities and differences of different computations will not be discussed in this proceeding. Here, we utilize a Monte Carlo approach to compute the neutrino flux at production and integro-differential equation to propagate the neutrinos.

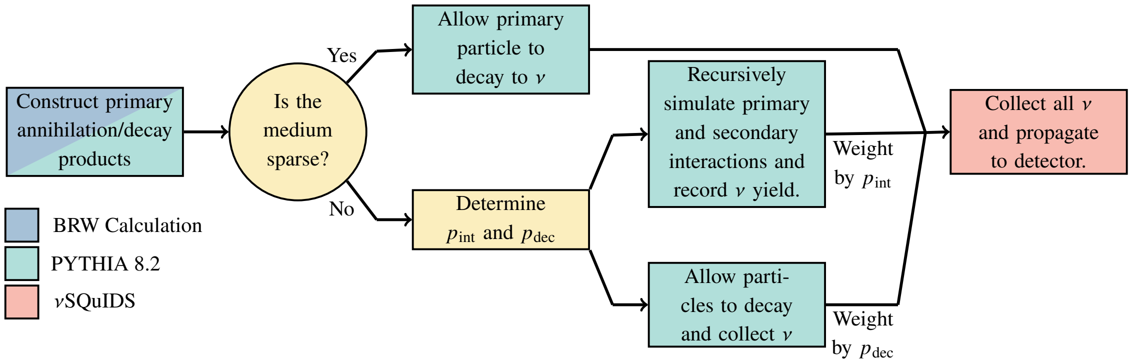

Figure 2: Flow chart depicting the major steps in the calculating flux from DM annihilation or decay. The light yellow boxes indicate direct calculation or decision making; other colors indicate the main program used in each step.

In this work, we introduce a new tool, χarov[1], to compute the neutrino fluxes from WIMP annihilations and decays in the Sun, the Earth, and the Galactic Halo. For DM masses below the electroweak (EW) scale, the neutrino flux produced from DM annihilation or decay is computed using PYTHIA-8.2, while for masses above this scale a recent calculation by Bauer, Rodd, and Webber (BRW) [11] is used. The propagation of neutrinos from their production region to the detector is computed with the help of the neutrino propagation software νSQuIDS[2] (developed from SQuIDS [12]). A high-level diagram of this process is shown in Fig. 2.

2. Neutrino Production

The expected neutrino flux at detector from the Galactic Halo for a DM with mass m_χ is expected to be

$$\Phi_{\nu,\rm det} = \frac{\Gamma_x}{4\pi m_\chi^a}\frac{dN_\nu}{dE_\nu}\int \rho^a(l,\theta)dl, \tag{1}$$

where dN_ν/dE_ν is neutrino yield, i.e. events per unit energy per annihilation or decay, and Γ_x is the interaction rate. The integral represents the sum of DM density over the line of sight and is referred to as the J-factor (annihilation) or D-factor (decay). For annihilation, $a = 2$ while $\Gamma_x = \langle\sigma_A v\rangle/\kappa$ where $\langle\sigma_A v\rangle$ is velocity distribution averaged cross section ($\kappa = 2$ for Majorana DM and 4 for Dirac DM); for decay, $a = 1$ and Γ_x is the inverse of the DM lifetime. The interactions of neutrinos when traveling through the interstellar medium are negligible and only the oscillation needs to be taken into account if we want to distinguish flavors. For celestial bodies which can been seen are point sources, the expected flux is

$$\Phi_{\nu,\rm det} = \frac{\Gamma_x}{4\pi d^2}\frac{dN_\nu}{dE_\nu}, \tag{2}$$

where d is the distance between the WIMP annihilation/decay location. Interactions and oscillations of neutrinos when traveling to the detector are not shown in Eq. (1) and Eq. (2), and will be discussed in Sec. 3.

[1]Pronounced Charon. χarov
[2]νSQuIDS

Here, we discuss the generation of the neutrino yield at the production site. We focus the discussion on the annihilation since the decay scenario only has a factor of 2 difference. Since the interaction of DM with the SM is unknown, we take the pragmatic approach of computing the neutrino spectra for DM annihilation to $q\bar{q}$, gg, W^+W^-, Z^0Z^0, HH, l^+l^-, and direct neutrino channels $\nu_\alpha\bar{\nu}_\alpha$. Here, $q\bar{q}$ are the six quarks, l^+l^- are the three charged leptons, and $\nu_\alpha\bar{\nu}_\alpha$ are the three neutrino flavors. The neutrino yield depends on the interplay of two variables: the primary particles produced and the environment in which production takes place. In sparse environments, those where the interaction lengths of particles are much longer than decay lengths, neutrinos can be formed as the primary decay or annihilation products, or as secondary products produced after the primary particle hadronizes and showers.

In dense environments, on the other hand, this condition is not satisfied; the competition between interactions of the produced particles with matter and their decay process modifies the final neutrino spectrum. Therefore, one must compute the secondary particles' interaction lengths in order to predict the neutrino fluxes. In this work, we compute the fluxes at production using PYTHIA 8.2 with some modifications, since a vacuum environment is assumed by default in PYTHIA. Except the top quark, which will immediately decay, all quarks will promptly hadronize. The resulting hadrons will lose energy in the production environment so the interaction lengths have to be compared to the decay lengths to determine whether the decay can happen. When the interaction and decay times are comparable, which is the case of hadrons that contain b or c valence quarks, we weight our simulation according to the rate of these two processes and apply energy loss. For charged leptons, it is safe to estimate τ decays immediately since the energy loss rate is negligible until the energy becomes high energy, e.g. $\gtrsim 10^9$ GeV in the Earth. Long-lived particles, $\pi^\pm$, $K^\pm$, K_L^0, neutrons and $\mu^\pm$, are either fully absorbed by matter or decay after being stopped which contributes to the sub-GeV flux [13].

For DM masses above the electroweak (EW) scale, the neutrino flux generation in χarov is coupled to a new computation of the EW correction which also accounts for polarization of annihilation and decay states and the evolution of the polarized particles to the EW scale [11]. As EW interactions are only partially implemented in PYTHIA, this calculation incorporates a more complete consideration such as the missing triple gauge couplings in the EW sector. Polarization and EW correction effects are also implemented in PPPC, which takes a different approach by augmenting the leading order EW correction term [14]. The inclusion of this new estimation of EW corrections and polarization gives rise to different spectra. For WIMP masses above 500 GeV, we use the BRW calculation of the initial flux.

3. Neutrino Propagation

The νSQuIDS software is used to consistently account for the above effects in neutrino transport. This package represents the initial flavor in the density matrix formalism. With flux of flavor α specified by ϕ_α, $\rho = \sum_\alpha \phi_\alpha(E,x)\,|\nu_\alpha\rangle\,\langle\nu_\alpha|$, the evolution (shown here is the neutrino case ρ and the formalism is similar in the antineutrino case $\bar{\rho}$) is governed by

$$\frac{\partial\rho}{\partial r} = -i\,[H,\rho] - \{\Gamma,\rho\} + \int_E^\infty F(\rho,\bar{\rho},x,E',E)dE', \tag{3}$$

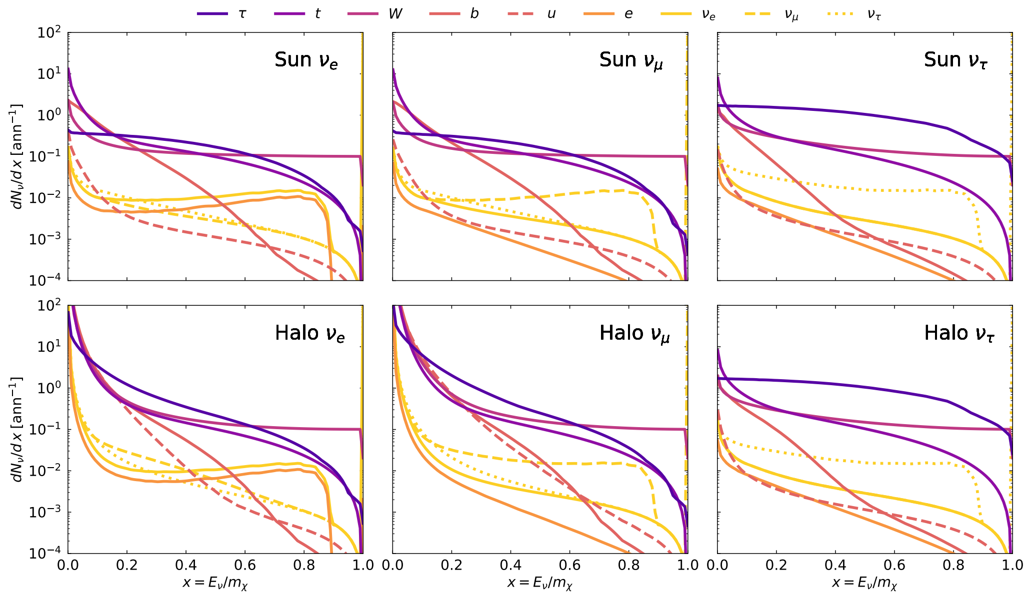

Figure 3: Spectra at production for several representative annihilation channels, indicated by different line colors for a DM mass of $m_\chi = 1$ TeV with EW correction and without decays from stopped particles. Different polarization states are averaged over. The top row corresponds to the center of the Sun, while the bottom row is for the Galactic Halo. The different columns indicate the neutrino flavors.

where H is the full neutrino Hamiltonian, including both the neutrino kinetic terms and matter potentials; Γ is the interaction rate which incorporates the effect of attenuation due to non-coherent interactions; and F is a functional which encodes the cascading down of neutrinos due to charged and neutral current processes. The terms in this equation depend on the environment traversed by the neutrino, as well as the PMNS matrix U and neutrino cross sections. For the nominal results and plots shown here the oscillation parameters to the best-fit values for normal ordering from NuFit-5.0 [15] and model the neutrino nucleon cross section using the `nuSIGMA` calculation [3].

The distance between the Galactic Center and the Earth is sufficiently large that all current and next-generation detectors do not have sufficient energy resolution to resolve individual oscillations. In this regime, the flavor transition probabilities are given by the average values. Neutrinos produced in the solar center must travel through solar matter, vacuum, Earth's atmosphere, and the Earth itself to get the detector while the neutrino flux from Earth WIMPs propagates from the Earth center to the detector. Here, the standard solar model given in [16] is used as the profile for neutrino propagation from center of the Sun to the surface of the Sun and the Earth density and composition is parameterized by the Preliminary Reference Earth Model (PREM) [17]. ν`SQuIDS` accounts for matter effects in this process. Assuming the DM is at rest relative to the Sun, the neutrino flux will be emitted isotropically. To compute the expected flux at the detector, one must consider both the detector position and the Earth's position relative to the Sun. We can compute the time-dependent flux which changes with the solar zenith angle, as well as the time-integrated flux which depends on the time window. For the Earth flux, there is no such time-dependent information.

[3] `nuSIGMA`

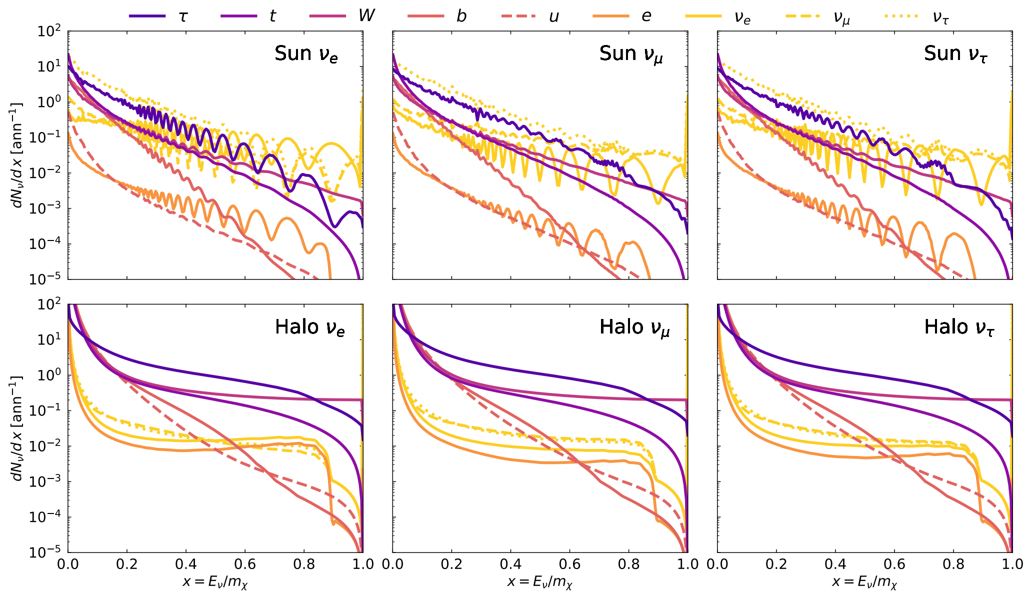

Figure 4: Neutrino flux from DM annihilation at Earth's surface. Colors and line styles have the same meaning as in Fig. 3. Results in the top panel are computed with a zenith angle of 60° while those in the bottom panel are computed with a zenith angle of 0°. Oscillation parameters used here are from nuFIT 5.0 normal ordering [15].

4. Secluded DM

In an alternative scenario, DM particles are assumed to be *secluded* from the SM [18]. Secluded DM interacts with the SM through a dark-sector mediator while direct couplings to the SM are greatly suppressed. In this model, DM annihilates to a pair of long-lived mediators, ϕ, which then decay to two pairs of SM particles. These SM particles will then decay to stable messenger particles as discussed previously. A sketch is shown in the right panel of Fig. 1, which can be compared to the left panel.

This model includes two additional parameters besides m_χ when considering the spectrum generation: m_ϕ and λ_ϕ, the mass and decay length of the mediator. The introduction of λ_ϕ changes the production region from the point-like production region considered previously to an extended region, with the probability of SM particles being produced at a distance r from the center of the source given by $\frac{dP}{dr}(r) = \frac{e^{-r/\lambda_\phi}}{\lambda_\phi}$. The introduction of these new parameters affects the flux calculation in multiple ways. For example, the boost decides how collimated the flux is and how much it is softened. When λ_ϕ is larger than the radius of the neutrino-opaque environment, one can additionally look for other messengers as a DM signature.

To compute the initial flux, decays of a mediator to SM particles with an initial energy of $m_\chi/2$ are sampled over the production region. The mediators are assumed not to interact with matter on the way from the point of production to the point of decay. SM particle interactions are included if the decay happens inside the Sun or Earth. In this process, we use the approximation that the final neutrinos are collimated and move in the same direction as the mediator; therefore, we only consider fluxes along the line of sight. After obtaining the flux throughout the production region,

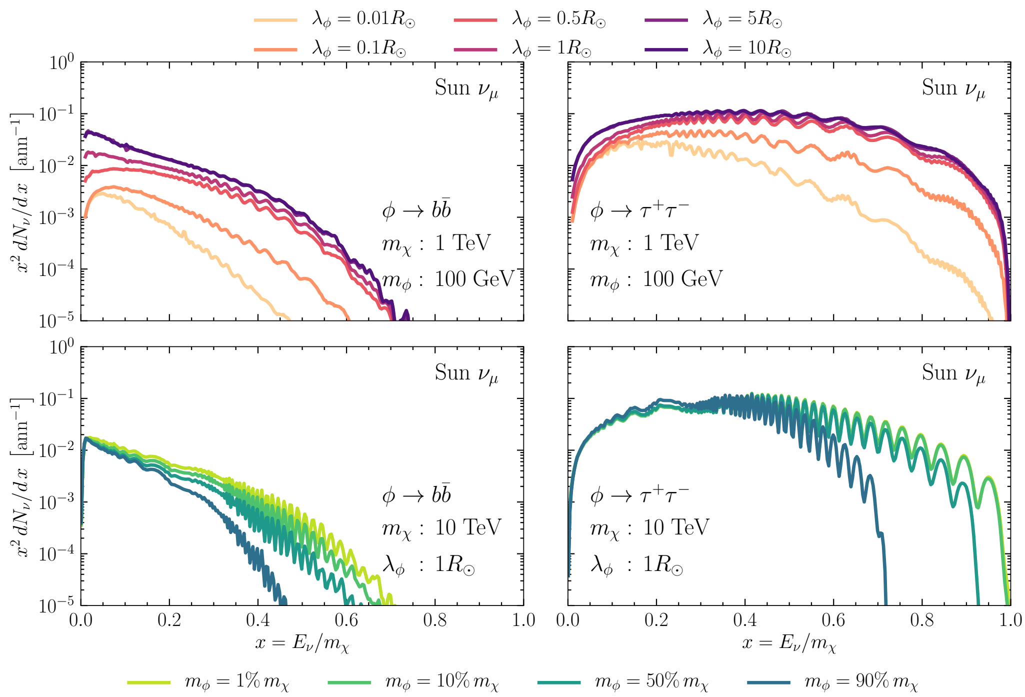

Figure 5: Solar secluded DM neutrino fluxes at 1 AU. In the left panels we show the muon neutrino spectrum for the $b\bar{b}$ channel and in the right panels the $\tau^+\tau^-$ channel. The top plots are meant to illustrate the dependence on the mediator decay length; for this we set the mediator mass to be 100 GeV and the DM mass 1 TeV. The different lines show different mediator decay lengths in units of the solar radius; where they are color-sorted from shortest to longest as they go from lighter to darker. The bottom plots are meant to illustrate the dependence on the mediator mass, for this we now set the decay length to be one solar radius and the DM mass to be 10 TeV. The different lines show different mediator mass, which we show as a fraction of the DM mass; color-sorted from lightest to heaviest as they go from lighter to darker.

we propagate it to the detector with an integral along the line of sight including the exponential distribution. Secluded DM in Sun is also discussed in `WimpSim` [9] and our results are comparable.

5. Summary

In this work we have computed the flux of neutrinos from DM decay and annihilation both in the standard WIMP paradigm as well as in the secluded DM scenario. Our calculation includes several updates over previous results such as new EW corrections for neutrino production, as well as a new propagation tool that is flexible and allows one to vary environment and parameters, such as the neutrino oscillation parameters and neutrino-nucleon cross sections. Additionally, we include the possibility of the secluded DM scenario in the Sun and Earth. Our resulting fluxes below the EW scale are in good agreement with the `WimpSim` calculation. Additionally, our code also supports the secluded DM scenario, where DM annihilates to an unstable long-lived mediator which in turn decays to SM particles. For completeness, our package additionally contains a calculation of the WIMP capture rate in the Sun and Earth and a computation of the J/D-factor to be used for the Galactic contribution. To be flexible, the package is able to handle for example oscillation parameters and external input of the initial flux, neutrino interaction cross sections and density profiles. More details of the package and comparisons are described in [19].

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