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Monochromatic neutrino signals from dark matter annihilation

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ABSTRACT

Dark matter (DM) annihilations in the Sun to neutrino–antineutrino pairs are known to have potentially observable signatures in neutrino telescopes such as IceCube and KM3. We propose a model independent analysis in which the monochomatic neutrino signal from dark matter (DM) annihilations in the Sun is related to the direct detection spin-independent and spin-dependent cross sections rather than assuming cross sections from a particular model. We propagate the neutrinos from the center of the Sun to the Earth taking into account matter effects on neutrino oscillations. For DM capture in the Sun via a large spin-dependent DM capture cross section the discovery prospects of the IceCube experiment are found to be promising.

1. Introduction

Dark matter is perhaps the best evidence for physics beyond the Standard Model (SM). The amount of dark matter is known to be about 22% of the total matter-energy budget of the universe, while visible matter only comprises of about 4% of the universe [1]. Any realistic model of physics beyond the SM must supply a DM candidate that can reproduce the observed relic density and many models have been suggested that can yield a DM candidate. Generally, a parity in the model leads to a stable DM particle. The leading DM candidate is a neutral weakly interacting stable particle that was produced in the Big Bang.

Vigorous experimental efforts are underway to identify the nature of DM. A direct way to identify the DM particle is to observe the recoil of a nuclear target. A spin-independent (SI) interaction is probed by detecting the recoil of DM from high mass nucleus; the coherent interaction increases the total cross section substantially compared with light nuclei. The best current limit comes from the Xenon10 experiment which found an upper bound of 4.5×10^{-8} pb for a DM mass of ≈ 30 GeV [2]; it is expected that CDMS will soon improve on their current limit of 1.6×10^{-7} pb [3]. The spin-dependent (SD) interaction is governed by the spin of the nucleon. The upper limits from direct DM search on the SD cross section are 6 orders of magnitude weaker than SI with the best bound from ZEPLIN-II at 0.07 pb [4] for DM scattering on neutrons. The NAIAD, COUPP, and KIMS experiments have placed upper bounds on the cross section for SD scattering of dark matter on protons of 0.5, 0.3 and 0.2 pb, respectively, for a DM mass of order 100 GeV [5–7]. The Super-Kamiokande (SK) search for neutrinos from DM annihilations in the Sun places a stronger limit, albeit model dependent, on the SD cross section; converting the SK flux limit requires assumptions about the DM mass and the cross section for DM annihilation to neutrinos. For a DM mass of order 100 GeV the SK limits on the SI and SD cross sections are of order 10^{-5} and 10^{-2} pb, respectively [8,9]. For a recent discussions of various direct and indirect DM searches, see Refs. [10–12].

At the Large Hadron Collider (LHC), a characteristic signature of the DM particle will be missing transverse energy. Typically, the DM particle is created at the end of a cascade decay chain of new physics particles. The reconstruction of the mass of the DM particle at colliders is challenging but feasible.

Additionally, DM is being sought in astrophysics experiments through annihilations to γ-rays [13–17], antideuterons [18] and positrons [19–21] in the galactic halo.

The method of DM detection on which we concentrate in this study is the detection of muon neutrinos from DM annihilations in the Sun and Earth with km^2 size neutrino detectors [22,23]. Currently, the IceCube experiment at the South Pole is underway; it has a muon energy threshold of about 50 GeV [24,25]. The planned km^2 size detector in the Mediterranean Sea, known as KM3 [26], should detect neutrino interactions above a 10 GeV muon energy threshold.

DM is expected to be gravitationally captured in the core of the Sun and Earth and subsequently annihilate. The rate of capture is strongly dependent on the SD and SI scattering rates that are being limited by direct detection experiments. For DM capture in the Sun, the SD cross section is the dominant interaction since the Sun is primarily composed of Hydrogen which has a net spin. The

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situation for the Earth is very different as the contributions to the capture rate via the SD interaction are negligible for heavy nuclei. Overall, since the SD cross section is nearly 6 orders of magnitude less constrained than the SI cross section, models that predict large SD rates have greater potential to yield an observable neutrino flux from DM annihilations in the Sun.

The study of the properties of DM annihilations to neutrino pairs has advantages over a more general neutrino spectrum. The injected neutrino spectra from this simple process consists of a line at $E_\nu = M_{\rm DM}$.[1] Models in which a neutrino line spectrum from DM annihilations can be realized include a Dirac fermion [27], Kaluza–Klein spin-1 boson [28,29] and a scalar [30] that couples to a new vector field. In this Letter we follow a model independent approach and take into account the effects on neutrino propagation through matter, following the methods of Ref. [12], focusing on the $\nu\nu$ annihilation channel.

The solar capture rate of dark matter in the galactic halo is approximately given by [31]

$$C_\odot = 3.4\times 10^{20}\ {\rm s}^{-1}\left(\frac{\rho_{\rm local}}{0.3\ {\rm GeV/cm^3}}\right)\left(\frac{270\ {\rm km/s}}{v_{\rm local}}\right)^3 \times\left(\frac{\sigma_{\rm cap}}{10^{-6}\ {\rm pb}}\right)\left(\frac{100\ {\rm GeV}}{M_{\rm DM}}\right)^2, \tag{1}$$

where $\rho_{\rm local}$ and $v_{\rm local}$ are the local density and velocity of relic dark matter, respectively. The average density of $\rho_{\rm local} \approx 0.3\ {\rm GeV/cm^3}$ may be enhanced due to caustics in the galactic plane [32]. The effective strength of the capture cross section of DM with solar matter is given by $\sigma_{\rm cap} = \sigma^{\rm H}_{\rm SD} + \sigma^{\rm H}_{\rm SI} + 0.07\sigma^{\rm He}_{\rm SI}$. The factor of 0.07 before $\sigma^{\rm He}_{\rm SI}$ comes from the relative abundance of helium and hydrogen in the Sun, as well as other dynamical and form factor effects [33]. The cross sections determine how efficiently the Sun slows and captures DM. The value of $\sigma_{\rm cap}$ has considerable variation with models.

The capture rate of dark matter in the galactic halo by the Earth is approximately given by [34]

$$C_\oplus = 4.8\times 10^{13}\ {\rm s}^{-1}\left(\frac{\rho_{\rm local}}{0.3\ {\rm GeV/cm^3}}\right) f_\oplus(M_{\rm DM}) \times\left(\frac{\sigma_{\rm cap}}{10^{-6}\ {\rm pb}}\right)\left(\frac{\mu_{p-{\rm DM}}}{1\ {\rm GeV}}\right)^{-2}, \tag{2}$$

where $\mu_{p-{\rm DM}} = \frac{M_{\rm DM} m_p}{M_{\rm DM}+m_p}$ is the reduced mass of the DM-nucleon system and $\sigma_{\rm cap} = \sigma^{\rm H}_{\rm SI}$. The form factor, $f_\oplus(M_{\rm DM})$, is given in Ref. [34]. A positive signal from the Earth, but not the Sun would strongly suggest that the DM particle has no significant SD interaction with matter.

Our analysis is model independent in that we relate the neutrino signal to the direct detection SD and SI cross sections rather than assume cross sections from a particular model, such as UED, as has been done in previous studies.

Other authors have discussed the neutrino line, particularly in context of Kaluza–Klein and right-handed neutrino models [35–37], but did not calculate the propagation of the neutrinos through the Sun. Instead, they assigned a probability of passing through the Sun that decays exponentially with neutrino energy. The emphasis of the model-independent analysis by Cirelli et al. [12] was on the shape of the neutrino spectra. We focus on the event rate at IceCube resulting from DM annihilations in the Sun to $\bar\nu\nu$.

[1] Using this injection spectrum, which can be taken as a delta function, one can reproduce any general spectrum after propagation via the Green's function of the evolution equation.

2. Neutrino production and propagation

We assume that DM annihilates at the capture rate to neutrino pairs with a democratic ratio of $\nu_e:\nu_\mu:\nu_\tau:\bar\nu_e:\bar\nu_\mu:\bar\nu_\tau = 1:1:1:1:1:1$, producing a characteristic line shape in the initial neutrino energy spectra. We included the full effects of neutrino oscillations and re-scattering processes described in Refs. [12] and [23].

The evolution equation is given by [12]

$$D_{\rm prop}\boldsymbol\rho \equiv \frac{d\boldsymbol\rho}{dr} + i[\boldsymbol H,\boldsymbol\rho] - \left.\frac{d\boldsymbol\rho}{dr}\right|_{\rm NC} - \left.\frac{d\boldsymbol\rho}{dr}\right|_{\rm CC} - \left.\frac{d\boldsymbol\rho}{dr}\right|_{\rm inj} = 0, \tag{3}$$

where $\boldsymbol\rho(r,E)$ is the complex density matrix in the gauge eigenbasis describing the state of the neutrino of energy E at a distance r from the center of the Sun. The Hamiltonian, $\boldsymbol H$, includes the effects of vacuum oscillation from nonzero neutrino mass splitting and the matter interaction:

$$\boldsymbol H = \frac{\boldsymbol m^\dagger \boldsymbol m}{2E_\nu} + \sqrt{2}G_F\left[N_e(r)\delta_{i1}\delta_{j1} - \frac{N_n(r)}{2}\delta_{ij}\right]. \tag{4}$$

Here $\boldsymbol m$ is the neutrino mass matrix in the gauge eigenstate basis, E_ν is the neutrino energy, $G_F = 1.66\times 10^{-5}\ {\rm GeV}^{-2}$ is the Fermi constant and $N_e(r)$ and $N_n(r)$ are the electron and neutron densities in the Sun [38]. The Neutral Current (NC) and Charged Current (CC) source terms describe the absorption and re-injection of neutrinos caused by NC and CC processes while the injection term describes the spectra injected from DM annihilation in the core of the Sun or Earth.

3. Muon rate at IceCube

We calculate the detection rates with up-going muons following the simulation for IceCube outlined in Ref. [39]. The neutrino flux at the surface of the Earth is given by

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{2}\frac{C}{4\pi R^2}\frac{1}{N}\frac{dN}{dE_\nu}{\rm BF}({\rm DM\,DM}\to\nu\bar\nu), \tag{5}$$

where the parameter C is the DM capture rate in the Sun ($C_\odot$) or Earth ($C_\oplus$) given explicitly above in Eqs. (1) and (2), respectively. The factor of $\frac{1}{2}$ is associated with the fact that two DM particles produce one annihilation event; here $R = 1.49\times 10^{11}$ m is the Earth–Sun distance for annihilation in the Sun, or $R = 6.4\times 10^6$ m is the radius of the Earth for annihilation in the Earth's core. The first factor in Eq. (5) describes the flux at the surface of the Earth while the $\frac{1}{N}\frac{dN}{dE_\nu}$ term is the normalized differential rate and ${\rm BF}({\rm DM\,DM}\to\nu\bar\nu)$ is the fraction of annihilations to neutrino–antineutrino pairs.

The muon rate in a km^2 area detector such as IceCube can be determined by folding the neutrino flux with the muon production cross section [23,33]

$$\frac{dN_\mu}{dE_\mu} = \int_{E_\mu}^{\infty}\frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}}\left[\frac{d\sigma^p_\nu(E_{\nu_\mu},E_\mu)}{dE_\mu}\rho_p + \frac{d\sigma^n_\nu(E_{\nu_\mu},E_\mu)}{dE_\mu}\rho_n\right] \times R_\mu(E_\mu)A_{\rm eff}(E_\mu)\,dE_{\nu_\mu} + (\nu_\mu\to\bar\nu_\mu). \tag{6}$$

The densities of protons and neutrons near the detector are $\rho_p = \frac{5}{9}N_A\ {\rm cm}^{-3}$ and $\rho_n = \frac{4}{9}N_A\ {\rm cm}^{-3}$, respectively, where N_A is Avagadro's number.[2] The muon range, $R_\mu(E_\mu)$, is the distance a muon travels before its energy falls below a threshold energy, $E^{\rm thr}_\mu$. We take $E^{\rm thr}_\mu = 50$ GeV, which is optimistic for IceCube, but the muon thresholds are expected greatly improve [40].

[2] Since the muon range is at most 1 km for a 1 TeV muon, the point of muon production can be assumed to be in ice, rather than the Earth's crust.