Simulation of neutrino signal from dark matter annihilation for JUNO experiment

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Abstract. Dark matter (DM) plays a major role in the large-scale structure formation of the universe. The leading candidate for DM particle is generally called Weakly Interacting Massive Particles (WIMPs) for its properties inferred from astronomical observations. Such DM particle would only interact via weak interaction and could decay or self-annihilate into other standard model particles such as ττ̅, uu̅, ee⁺, νν̅. In this work, we have simulated the final-state neutrino particles resulting from DM annihilations inside the Sun’s core. The neutrino propagations and oscillations to Earth and expected signals at the Jiangmen Underground Neutrino Observatory (JUNO) are then calculated. We will present the preliminary results of our study, including comparisons with various other neutrino sources to be detected at JUNO.

1. Introduction

The dark matter (DM) is one of the matter components in the universe. The current observation of cosmic microwave background (CMB) and lambda cold dark matter (ΛCDM) model show the percentage of the compositions in the universe: 4% of normal matter, 27% of dark matter and 69% of dark energy and also the existence of the DM [1]. However, it has not been detected directly by ground based detectors. There are a lots of theoretical DM candidates corresponding with the observational data and calculation. The promising DM candidate is Weakly Interacting Massive Particles (WIMPs) [2]. The DM can be detected through the standard model (SM) particle such as ττ̅, uu̅, ee⁺ and νν̅, indirect DM detection, or from the DM interaction via weak interaction with self-annihilation and decay.

The DM distributes all direction in the universe. The high density of DM in Milky Way galaxy is the center of our galaxy. Nevertheless, these signals are distant and difficult to distinguish from the other sources. The one of interested location for studying of DM is the Sun. The DM is captured by gravity of Sun’s core and it interacts itself and generate the SM particles [2].

We have simulated the neutrino particles in the final state decay from the SM particle that produced from capture DM annihilation inside the Sun’s core. Theses signal propagate to Jiangmen Underground Neutrino Observatory (JUNO) including the neutrino oscillation.

2. Jiangmen Underground Neutrino observatory (JUNO)

The Jiangmen Underground Neutrino Observation (JUNO) is under construction and anticipated to operate in 2020. It is located at the southern of China, Jiangmen city in Guangdong province [2]. The aims of JUNO experiment are to determine neutrino mass hierarchy, precisely measure oscillation
parameters, detect astrophysical neutrinos such as solar neutrinos, atmospheric neutrinos, supernova neutrinos, indirect dark matter neutrinos, geological neutrinos, etc. [2]. It consists of three mainly basic parts: the central detector, VETO and shielding, and electronics as shown in figure 1. The central detector comprises the liquid scintillator (LS) with 20 kilotons and surrounds with photomultiplier tube (PMT) to detect the photon from neutrino interaction with the LS [2]. The VETO and shielding consist of muon top tracker to measure muon direction, pure water tank to protect its detector from other radioactivity and PMTs to detect Cherenkov light, and indicating cosmic ray event [2]. The electronics part is very sensitive for dark noise of PMTs, instrumental material and effect from earth magnetic field. It is still developing [4].

![JUNO detector schematic](image)

**Figure 1.** Schematic view of JUNO detector [3].

The main channel of neutrino interaction with LS is inverse beta decay (IBD). The anti-electron neutrinos interact with the proton in LS and generate electron and neutron. The electron is annihilation and generate the prompt signal. The neutron capture on hydrogen (H) and generate the delay signal, around 200 ns [2]. These signals distinguish from the other particles interaction with LS.

### 3. Theoretical prediction

#### 3.1. Solar capture dark matter

The solar system is in the dark matter halo. The dark matter particle, WIMPs, can be captured by the gravitational force of the Sun and the earth. It is sunk into the centre of the Sun and the earth. The dark matter annihilation cross section is very small, $<\sigma v>\sim 3\times 10^{-23} \text{ cm}^3$ [5], it can annihilate themselves and generate to other types of SM particle and then decay into the neutrinos at the centre of the Sun and the earth. These neutrinos can be detected by the ground based detectors.

#### 3.2. Solar model

The solar model is necessary for simulating the neutrino signal when it passes through the sun. Although the neutrino is relativistic, weak interaction and have small mass, it is still able to have some interaction with the matter inside the Sun (neutron, proton and heavy atoms). This has an effect on the neutrinos oscillation. The element densities and opacity inside the Sun are considered as the function of sun radius [6].

#### 3.3. The neutrino signal

The differential neutrino flux of flavor $\beta$ (for $e$, $\mu$, $\tau$) from the dark matter annihilation into SM particle channels ($\chi\bar{\chi}\rightarrow f\bar{f}$) can be calculated [2]
\[
\frac{d\Phi_{\nu_i}^D}{dE_{\nu}} = P_{\nu_{\alpha} \rightarrow \nu_{\beta}}(E_{\nu}, D) \frac{\Gamma_A}{4\pi} \sum B_{\chi^2 2} \frac{dN_{\nu_{\alpha}}}{dE_{\nu}}
\]

(1)

Where \( \Gamma_A \) is the DM annihilation rate, \( B_{\chi^2 2} \) is the branching ratio for the DM annihilation channel \( (\chi \chi \rightarrow f \bar{f}) \), \( D \) is the distance between the source and detector, \( dN_{\nu_{\alpha}}/dE_{\nu} \) is defined as the energy spectrum of \( \nu_{\alpha} \) (for \( \alpha = e, \mu, \tau \)) and \( P_{\nu_{\alpha} \rightarrow \nu_{\beta}}(E_{\nu}, D) \) is the neutrino oscillation probability from the source to the detector. In this work we focus on three DM density profiles, Navarro-Frenk-White (NFW) [7], Burkert [7], and Einasto profile [5]. \( \Gamma_A \) can be calculated using the DM captured rate inside sun’s core \( (C_c) \) which depends linearly on the DM-nucleus scattering cross section, DM density profile, velocity dispersion of WIMPs and WIMPs mass [2] as shown in figure 2.

**Figure 2.** The annihilation rate inside the sun’s core as a function of WIMPs mass particle. The blue line is annihilation rate using the Burkert profile, green line is using the NFW profile and orange line is using Einasto profile with spin dependent DM-H scattering cross section = 1 pb [2].

The neutrino energy spectrum is calculated by Wimpsim package [6]. These signals include the neutrino oscillation which are shown in figure 3.
Figure 3. The electron neutrino spectrum with the ratio of neutrino energy and mass of WIMPs in the sun’s core and 1 AU by using 10 GeV and 1000 GeV, (a), (b), (c), and (d) respectively. Each of colour lines are different particle channels from DM annihilation.

The neutrino energy spectrum from the WIMPSIM package generate three flavour neutrino including anti-neutrino signal. Moreover, we simulated the neutrino signal at the Sun’s core, the Sun’s surface, at the earth (1 AU) and specific location of detector. However, the choices of target material of detector in WIMPSIM are only ice/water and rock.

4. Ongoing and future work
The JUNO software framework allows users to develop their own codes but it is quite dangerous to other codes or programs. Therefore, we have to create another physics generator on the JUNO software framework, the dark matter generator, by adapting code of solar neutrino generator and uses the neutrino energy spectrum from the WIMPSIM package instead.

Figure 4. The Diagram of JUNO software framework. The physics generator is a gun particle and simulate the neutrino signal after colliding with LS. The detector simulation generates the signal when the photon encountered PMTs.

The format of the neutrino energy spectrum from WIMPSIM package is altered for consistent JUNO detector simulation by writing the algorithm of GtDmTool.

5. Discuss and summary
The astrophysics objects are neutrino sources. However, the shape of neutrino spectrum are differences due to sources. Therefore, the neutrino signal can be used for indirect DM detection. JUNO experiment is ongoing as one of the neutrino detector. These spectra are different according to the WIMPs mass, the channel, and the location that have an effect from the neutrino oscillation, neutrino-nucleon cross section and tau decay.

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