Photon signal from non-interacting scalar dark matter annihilation

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Abstract. One proposal to search for Dark Matter is to look for photon signals which originates from DM annihilation. This is usually referred to as indirect detection experiment. In the case of Non-Interacting Scalar Dark Matter, there are no electromagnetic, strong, and weak interactions. Thus, the DM only interacts gravitationally. In our model, we determine the NISDM annihilation into a virtual graviton which subsequently creates a pair of Higgs bosons. The Higgs boson then suddenly decays into two photons. The line of sight integral is considered as a significant effect of the DM halos density profile. The total cross-section, thermally averaged cross-section and photon signal are finally calculated and illustrated.

1. Introduction

In general, most of the cosmic ray detections is through searching for photons or leptons, due to spontaneous decay of heavy particles. Therefore, the light particles can be detected efficiently and straightforwardly. Consequently, photons or \(\gamma\)-rays are valuable signals for astronomical observations.

Despite the fact that Dark Matter does not interact electromagnetically, an out-going photons final state can occur in some annihilation processes. Regularly, the out-going photons are created in loop level. Additionally, The subsequent decay of the DM annihilation’s products is another postulation for that creation. Moreover, the properties of the model become essential constraints to generate possible interactions. In case of Non-Interacting Scalar Dark Matter (NISDM), there is only gravitational interaction around it, which makes the graviton-scalar coupling model an important role in the annihilation process. From G. ’t Hooft’s and M. Velmann’s work [1], we knew that leading-order of gravity cannot be calculated. We thus consider the case that a pair of Higgs boson is the annihilation’s product. The Higgs bosons then subsequently decay into a pair of photons.

After the photons final state is created, we study the scattering signature by considering the scattering cross-section. In terms of astroparticle physics, the cross-section is not enough to evaluate the photon signal. We thus need to consider both thermally averaged cross-section and J-factor [2]. In this research, we show the simplification of the cross-section formulas by including some experimental results which are verified. We finally calculate and illustrate the differential flux of \(\gamma\)-rays or photons at the Earth by including the effects from the Dark Matter halos density profile.
Figure 1. The left diagram describes the Dark Matter annihilation into unstable Higgs boson before the photon creation. The right diagram shows the energy-momentum flow of the annihilation process.

2. Methodology

When the Dark Matter only interacts gravitationally, the graviton - scalar coupling model will play an important role in scattering amplitude calculation. In the low-intensity limit of the gravitational field, the graviton is described as the quantization of gravitational radiation. The Feynman rules of the model are given by

\begin{align}
  P^{\mu\nu\alpha\beta}(q) &= \frac{i}{q^2 + i\epsilon} [\eta^{\mu\alpha}\eta^{\nu\beta} + \eta^{\mu\alpha}\eta^{\rho\beta} - \eta^{\rho\nu}\eta^{\mu\beta}] \\
  \tau_{\mu\nu}(p_f, p_i) &= -\frac{i\kappa}{2} [p_{f\mu}p_{i\nu} + p_{f\nu}p_{i\mu} - \eta_{\mu\nu}(p_f \cdot p_i - M^2)]
\end{align}

where the \( \kappa = \sqrt{8\pi G} \), G is the gravitational constant \( (6.7 \times 10^{-39}\text{GeV}^{-2}) \). Four out-going photons can be obtained by considering figure 1. Theoretically, Higgs boson does not decay directly into photons but also decay in one-loop level which is a massive calculation and cannot be determined straightforwardly (figure 2). Nevertheless, the simplification of the scattering amplitude was clearly showed that the process of \( \chi\chi \rightarrow \gamma\gamma \) can be separated into two subprocesses [3].

\begin{align}
  iM_{\chi\chi\rightarrow\gamma\gamma} &= \frac{(Gf_{H\gamma\gamma}^{\mu\nu})^{\alpha\beta}}{iM_{H\rightarrow\gamma\gamma}} P_3^\mu P_4^\nu P_3^\rho P_4^\sigma \left[ \frac{i}{iM_{H\rightarrow\gamma\gamma}} \langle 0 \rightarrow \gamma\gamma \rangle \right] \left[ \frac{i}{iM_{\chi\chi\rightarrow HH}} \langle 0 \rightarrow \chi\chi \rangle \right]
\end{align}

Figure 2. The effective Higgs-two-photons vertex which is compounded from considerable loop corrections. The branching ratio of \( H \rightarrow \gamma\gamma \) channel \( \approx 10^{-3} \), which is smaller than other channels [4].

From the scattering amplitude (3), the scattering cross-section can be rewritten as the product of the Dark Matter scattering and the Higgs decays. Moreover, the loop corrections also affect the Higgs propagator, which makes the mass pole or Breit-Wigner mass on the propagators [3,5,6].

\begin{align}
  \sigma_{\chi\chi\rightarrow\gamma\gamma} &\approx BR_{H\rightarrow\gamma\gamma}^2 \sigma_{\chi\chi\rightarrow HH} \bigg|_{p_3^2 p_4^2 = M_H^2}
\end{align}
where $BR$ is the Higgs decay into a pair of photons branching ratio. However, the scattering cross-section is not enough for the photons flux evaluation. The differential flux of the DM annihilation is given by [2,7]

$$
\frac{d^2\Phi_\gamma}{dE d\Omega_\gamma} = \frac{1}{4\pi} \frac{1}{2M^2} \sum_{i} \langle \sigma_i \cdot v \rangle \frac{dN_i}{dE_\gamma} \times \frac{1}{4\pi} \int \rho_{DM}[r(l)] dl
$$

(5)

where $\langle \sigma \cdot v \rangle$ is the annihilation rate, $J$ is the line of sight integral, and $dN/dE$ is the number of the particles (N) at the energy (E). In this work, we consider commonly used model profiles for DM halos.

3. Results

We separate the cross-section into two cases to study the scattering signatures in each region of Dark Matter mass. The thermally averaged cross-section $\langle \sigma \cdot v \rangle$, which is one of the main ingredients of the photon flux calculation, is then computed. In this work, we consider only Cold Dark Matter (CDM), which is a hypothetical structure of DM halos. The initial momentum of the DM therefore tends to zero $p_\chi \rightarrow 0$. The results are shown in figure 3.

In terms of the differential flux of photon calculation, we approximate the spectral energy distribution $dN/dE$ as a delta-function at contained energy-momentum of the Higgs boson. The NFW and Burkert Dark Matter density profile are considered as hypotheses of the DM halos.

![Figure 3](image)

Figure 3. The total scattering cross-section of $\chi\chi \rightarrow 4\gamma$ in the different DM masses. The case that $M_{DM} < M_H$ (100 GeV) is shown in (a) and the other (175 GeV) in (b). Thermally averaged cross-section of the 4$\gamma$ channel (c). The branching ratio’s uncertainty provides error bounds.
Figure 4. The theoretical differential flux of $\gamma$-rays which are detected at Earth. (a) is the observation point at $\pi/2$ and (b) at $\pi/4$, where the DM density can be simplified as a function of angle which respects to the direction of the Earth to the Galactic Center.

4. Discussion and conclusion
The total and thermally averaged cross-section give us both the scattering signature and probability density. The total cross-section obviously shows that the mass of Dark Matter provides different annihilation behavior. The probability density for fining the scattering process increases constantly and tends to a similar trend at the high-energy region. The thermally averaged cross-section is also computed to be the ingredient for the differential flux of photons equation(5). In the case of CDM, the trend of thermally averaged cross-section increases when DM contains huge mass, and also shows the scattering at threshold energy (figure 3).

The thermal average of cross-section directly affects the differential flux even though it is only one of the components. There is a significant increase in the threshold energy regions. The flux trends then increase constantly in the high-energy region. The results illustrate that the photons from this model probably detected as ultra-high-energy $\gamma$-rays.

Moreover, the Dark Matter profiles also affect the flux calculation. Figure 4 shows that the differential flux also depends on the angle between the direction of the line of sight and the axis connecting the Earth to the Galactic Center.

In conclusion, there are significant differences in both the scattering signature and the photon signal between DM and NISDM. In general, DM thermally averaged cross-sections are usually in the $10^{-20}$ to $10^{-30}$ $cm^3/s$ region and its photon flux trends often decrease and vanish at high-energy region [2,7]. Nevertheless, The NISDM annihilation provides the tiny photon signal which is proportional to gravitational constant. Moreover, the differential flux also increases at high-energy regions, which is probably the effect of graviton-scalar coupling model.

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